Queen Mary
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Sea-level changes in south east England and northern France

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2002

Thesis submitted for the degree of Doctor of Philosophy

Abstract

The aim of the research was to provide new sea-level index points, with the intention of identifying any cross-channel similarities and comparing the results to geophysical models of relative sea-level change.

The research successfully provided new sea-level index points from the Pevensey Levels, East Sussex; the Canche Estuary, Pas de Calais and the Somme Estuary, Picardie, which were validated using stratigraphic, pollen, diatom, foraminiferal and AMS radiocarbon dating analysis.

The results pointed to the presence of a coastal barrier throughout the mid-Holocene at Pevensey and the Somme, which complicated the pattern of coastal sedimentation observed at these sites. A clear pattern of barrier de-stabilisation can be seen to take place either side of the Channel *c.* 3000 cal years BP. A cross-channel comparison identified three similar transgressive events either side of the English Channel, *c.* 5500, 3000 and 2200 cal years BP.

The observed results from each site were then compared to the predicted data (Lambeck *pers. comm.)* in order to determine whether the observational data could be used to validate the modelled data. The comparisons showed that for the sites in south east England the modelled data tended to over-predict sea-level rise for the mid- to late-Holocene, whereas the model tended to under-predict sea-level rise for the sites in northern France. The new observational data, which the research provided could be used to further validate Lambeck's (1990, 1997) geophysical model.

The effects of local coastal processes, such as tidal range, crustal subsidence and barrier-dynamics, were used to aid the comparisons between the pattern of sediment deposition and thus the sea-level signals. These findings suggested that reconstructions should be restricted to sites at an estuary-sized scale.

Statement of Originality

I certify that this thesis, and the research to which it refers, are the product of my own work, and that any ideas or quotations from the work of other people, published or otherwise, are fully acknowledged in accordance with the standard referencing practices of the discipline.

The results of the geophysical modelling in Chapter Eight rely heavily on the data provided by Prof. Lambeck, the use of which has been fully referenced. In addition to this, the results of the diatom-based transfer function discussed in Chapters Four, Five and Six, were provided by Dr. Zong. I am indebted to both Prof. Lambeck and Dr. Zong for allowing me to make use of these unpublished results.

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ACKNOWLEDGMENTS

I would like to thank my supervisors Dr Jeff Blackford, Dr Jim Innes and Dr Murray Gray for the expertise and comments they have provided, together with Graeme Butterfield for his continual encouragement. I would also like to thank everyone who assisted me with the collection of the field data in the UK and France: Samir Yousuf, Gillian Old, John Moore, Tim Davie, Jeff Blackford, Simon Cadby, Stewart Clarke, Megan Ellershaw, Jim Innes and Abigail Kelly. I am grateful to the awarding bodies who partly funded the fieldwork: Quaternary Research Association Young Workers Award, Bill Bishop Memorial Trust, The Dudley Stamp Memorial Trust and the British Geomorphological Research Group. I would also like to thank all the landowners in both the UK and France, especially to Mme Fauquet-Barbier at the Somme and Mr Norris Jnr and Mr Pugh at Pevensey. Also to NERC Radiocarbon Laboratory who funded all the radiocarbon dates. A huge thank you to the cartographer at Queen Mary, Edward Oliver, whose input was invaluable together with Dr Simon Haslett, for his assistance with the foraminiferal identifications. I am indebted to Dr Zong for his assistance with the diatom-based transfer function and to Prof. Lambeck for permitting the use of unpublished predicted sea-level data. The hard working and kind natured Sean Kim made the final few days so much easier than they would have been – many thanks! Thank you to everyone at Queen Mary, in particular Marta Timoncini for keeping my spirits high in the final few months. Lastly, I wish to say a special thank you to my fiancé, Samir and to my family for providing me with so much support over the past four years.

Chapter One Introduction

1.1 Introduction

This research aims to provides new sea-level data from three sites; the Pevensey Levels, East Sussex in south east England and the Canche and Somme estuaries in northern France. The project employs a multi-proxy approach, using lithostratigraphic and biostratigraphic data to construct sea-level curves for the three sites. The data are then used to carry out a cross-channel comparison in order to determine whether similar periods of marine transgressions can be seen either side of the Channel. In addition to this the observational data will then be used to test and constrain geophysical models of relative sea-level change (Lambeck, 1997, 1999, *pers. comm.*).

1.2 Why is the study of Late Holocene sea-level change important?

Understanding sea-level change is a current issue not only within Quaternary and coastal sciences, but also in the wider arena of global environmental change. The mid to late Holocene period has witnessed a shift in global climate and a subsequent rise in mean sea-level. The Holocene period has been dominated by a rising eustatic sea-level, referred to as the Holocene transgression. The post-glacial rise in sea-level was initially rapid. Across Europe and North America, sea-level rose by approximately 25m between the last glacial maximum *c.*15000 years ago and the mid-Holocene *c.* 7000 years BP (Kidson, 1980). This early-Holocene phenomenon was however replaced by a shift to a more gently rising sea-level *c.* 7000 ^{14}C yr BP. Long (2000) attributed the rapid mid-Holocene change to a reduction in the amount of meltwater discharge and a reduction in the Antarctic contribution. At many far-field sites the rate of sedimentation exceeded the rate of sea-level rise throughout this period. A third major Holocene shift can then be seen to take place *c.* 2000 ^{14}C yrs BP represented by a return to more rapidly rising sea-level (Long, 2000). However, as Long (2000) discusses, obtaining reliably dated late-Holocene transgressive overlaps from Europe is complicated by the pattern of coastal sedimentation and thus the present data are insufficient to draw precise conclusions.

In the last few decades however, collection of sea-level data has been widespread and clear patterns of relative sea-level change can be observed. It is estimated that global mean temperature has risen by 0.6° C and sea-level has risen by 1.0 to 2.0 mm/yr during the 20th century (IPCC, 2001 Technical Summary of Working Group One p.31). Fig. 1.1 shows a global average of relative sea-level rise and provides a possible future scenario. The causes of the rapid rise, of up to 0.2m in 20 years, can be attributed in part to anthropogenic influences, but more significantly to the natural variablilty of the climate system (IPCC, 2001). The IPCC identifies a number of sources that contribute to the future rise in sea-level. These include thermal oceanic expansion (0.11 to 0.43 m), a contribution resulting from glacier melting (0.01 to 0.23 m); the melting of the Greenland ice sheet (0.02 to 0.09 m); and lastly the melting of the Antarctic ice sheet (0.17 to 0.02 m).

The IPCC highlights the importance of anthropogenic radiative forcing as a means of altering climate and includes such factors as the increases in Carbon Dioxide, Methane, Nitrous Oxide and Sulphur as sources of change. Although it does not neglect the natural causes such as increased solar activity and volcanic eruptions, it concludes that anthropogenic factors have had a far greater impact during the 20th Century.

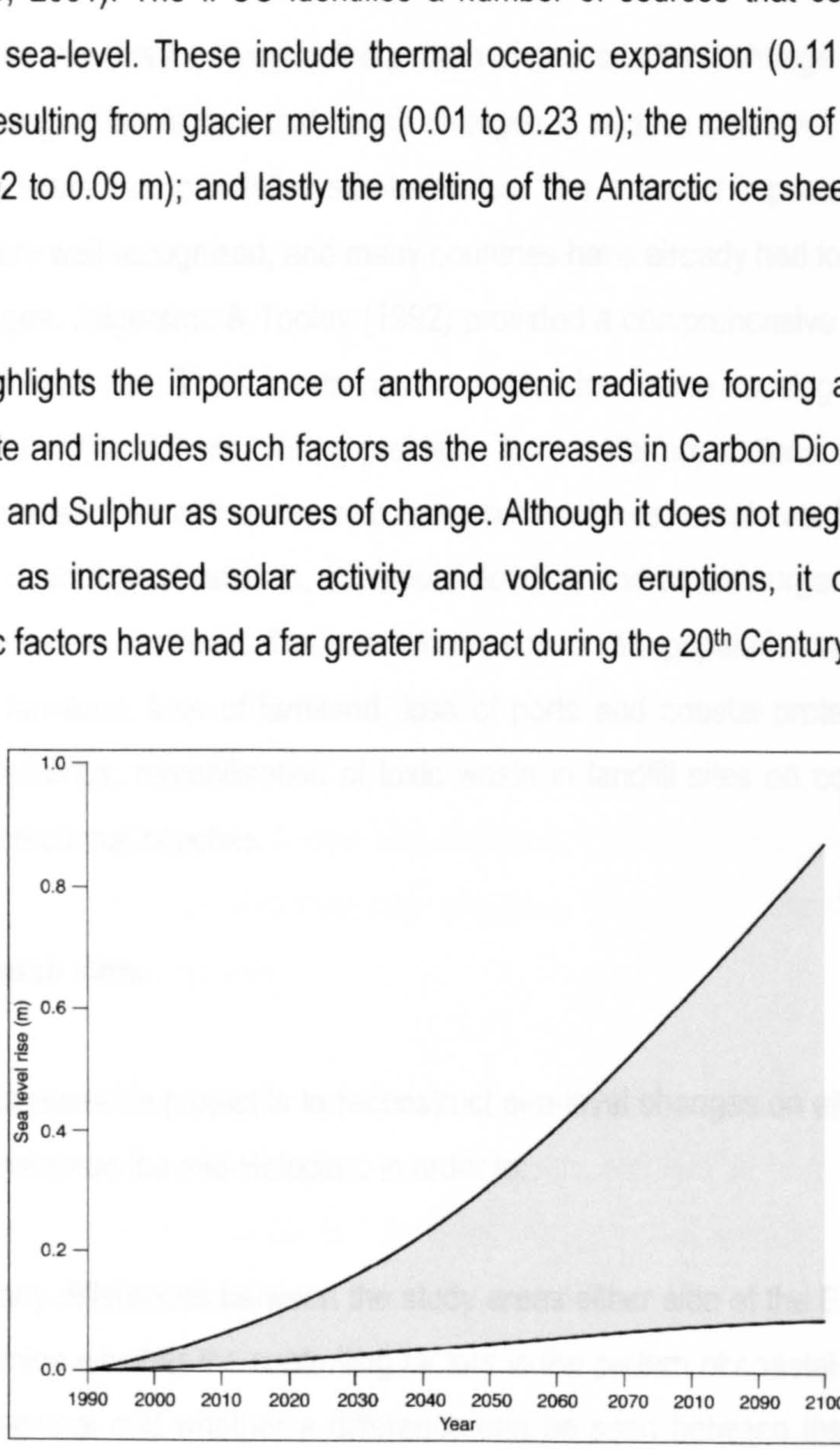

Fig. 1.1 Global average sea level rise between 1990 and 2100, represented by the range of all scenarios including uncertainty in land-ice changes, permafrost changes and sediment deposition After: IPCC (2001)

The IPCC (2001) stated that climate would affect the sea-level in a number of ways. The report predicts an increase in sea surface temperature and mean global sea-level, a decrease in sea ice cover and changes in salinity, ocean circulation and wave conditions (IPCC, 2001 Summary for Policy Makers p.11). The effects of any of these, or a combination of these, would have a devastating effect on coastal areas.

1.3 Impacts of future sea-level rise

One of the main reasons for studying the pattern of past sea-level change is to try to gain an understanding of the factors that cause changes in relative sea-level, and to try and determine the future rate of relative sea-level rise. The potential impacts of future sea-level change are well recognized, and many countries have already had to begin to adapt to these changes. Jelgersma & Tooley (1992) provided a comprehensive list of potential impacts of sea-level rise. The impacts can be divided into those causing damage to the natural environment and those posing problems for coastal populations. These impacts include the increased risk of inundation to reclaimed lowlands, accelerated rate of coastal erosion, loss of ecological habitats, increased flooding and storm surges and a shift in sedimentation in river upstream. The possible impacts on the population include saltwater intrusion into farmland, loss of farmland, loss of ports and coastal protection systems, disruption to fisheries, remobilisation of toxic waste in landfill sites on coastal lowlands and loss of recreational beaches.

1.4 Research aims

The aim of this research project is to reconstruct sea-level changes on either side of the English Channel since the mid-Holocene in order to:

a) Examine any differences between the study areas either side of the English Channel and determine whether the controlling factors in the pattern of coastal evolution were local or regional and whether a difference can be seen between the mid and late-Holocene
b) Determine the extent of past changes in relative sea-level over the mid- to late-Holocene and to provide an estimate of future sea-levels

c) Compare observed data with the data provided by the geophysical models of past relative sea-levels (Lambeck, 1997, *pers. comm.*) in order to provide new data which can be used to validate the models.

1.5 Methodologies available to carry out the research aims

One method of reconstructing past relative sea-levels involves the collection of sea-level index points; points for which altitude, age, indicative meaning and tendency are known. Initially, potential sea-level index points can be determined by observing lithostratigraphic changes between organic and inorganic sediments. However, in order for the indicative meaning (that is a specified tidal level such as Mean High Water Spring Tide) to be established, it becomes necessary to attach an environmental variable to the sediment. This is achieved through the quantification and identification of palaeoecological indicators, in this case pollen, diatoms and foraminifera. These points can then be used to construct sea-level curves in the form of age-altitude plots (Shennan, 1986; Haslett *et al.*, 1997, Shennan *et al.* 2000a).

In addition to the study of environmental records of sea-level changes, it is possible to model crustal properties, ice and water volumes and, hence, past relative sea-level positions (Mörner, 1987; Lambeck, 1990; Lambeck *et al.*, 1990 and Peltier, 1990). Once environmental data have been collected and analysed, it will then be possible to test and validate existing models of relative sea-level change by comparing observed data against predicted data for single estuaries.

Comparisons between the English and French coasts will be made using observed data collected from three sites, one in south east England and two in northern France, in conjunction with published sea-level data from both regions. This is being done in order to identify any cross-channel similarities in the timing of marine transgressions, so that a possible channel-wide link can be made. The observed sea-level data will then be compared to modelled data obtained for the same sites using specially compiled data (Lambeck *pers. comm.*).

1.6 Thesis structure

The thesis has been divided into nine chapters. Chapter One introduces the research project outlining the main aims and approaches. Chapter Two is subdivided into two sections. Section one provides an overview of the approaches to studying sea-level change describing all the lithostratigraphic and biostratigraphic techniques available. Section two presents a review of the evidence for late Holocene sea-level change on a global scale and then for southeast England and northwest France. Chapter Three describes the methodologies involved in carrying out the research and provides a description of the study sites. The results of the research have been divided into three chapters. Chapter Four presents the results from southeast England and Chapters Five and Six provide the results from the two sites in northern France. A cross-channel comparison of the results is performed in Chapter Seven and Chapter Eight compares the modelled with the predicted data. Finally Chapter Nine draws on the main conclusions found during the research. Fig. 1.2 shows the thesis structure diagrammatically.

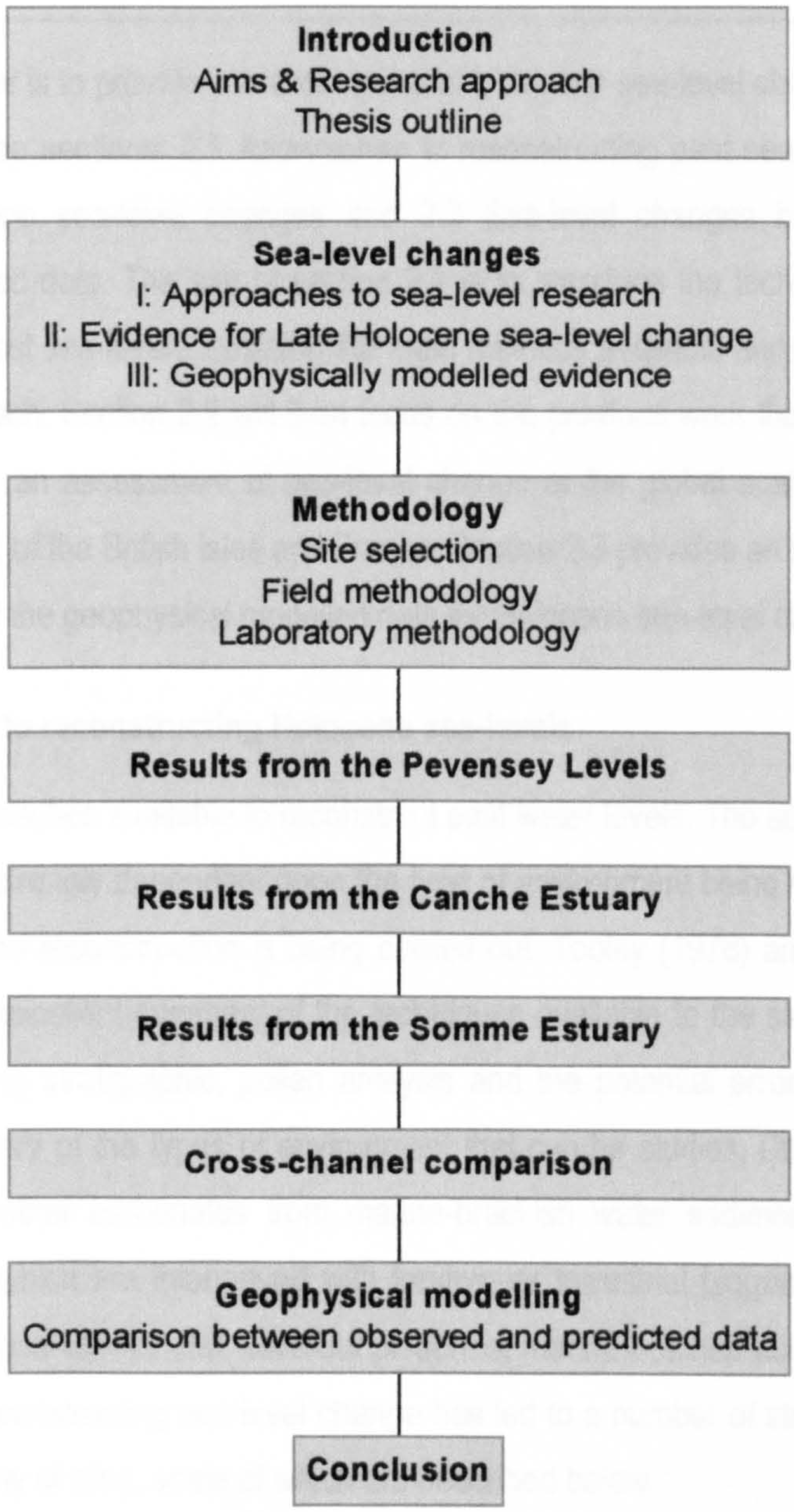

Fig. 1.2 Thesis structure

Chapter Two Sea-level Change

The aim of this chapter is to provide a critical review of Holocene sea-level change. It has been divided into three sections: 2.1 Approaches to reconstructing past sea-levels; 2.2 Evidence for Holocene sea-level changes and 2.3 Sea-level changes based upon geophysically modelled data. The aim of section 2.1 is to introduce the techniques that exist to reconstruct past sea-levels, outlining the main methods available and providing a critical appraisal of each. Section 2.2 will then focus on the previous work that has been carried out, providing an assessment of sea-level change at the global scale and then within the study areas of the British Isles and France. Section 2.3 provides an introduction of the main findings of the geophysical modelled data for Holocene sea-level change.

2.1 Approaches to reconstructing Holocene sea-levels

There are many approaches available to reconstruct past water levels. The application of these approaches is strongly dependent upon the type of environment being studied and the region in which the reconstruction is being carried out. Tooley (1978) and Shennan (1986b) provided an excellent summary of the techniques available to the study of sea-level change, including stratigraphic, pollen analysis and the potential errors involved. However for a summary of the types of environment that can be studies, Devoy (1987) includes shells and other carbonates from marine-brackish water sediments; marine inorganic sediments which are interleaved with freshwater terrestrial biogenic material; beach structures; palaeo-valleys and wave-cut platforms; marine notches and cliffs. The growing interest in reconstructing sea-level change has led to a number of studies being undertaken on a variety of sites, some of which are described below.

Lambeck (1993) appropriately stated that much of the palaeo sea-level evidence from England and Wales comes from river estuaries, shallow bays and low-lying coastal plains where sediments and organic materials have been deposited under tidal flat or lagoonal conditions. The method of studying litho- and bio-stratigraphic evidence of estuarine sediments is therefore often employed in England and Wales (Godwin, 1964; Devoy, 1979; Long & Innes, 1993; Zong & Horton, 1999; Andrews *et al.*, 2000). This approach involves the study of sites that were previously covered by the sea and have since been reclaimed. Sediments are identified, recorded and analysed for characteristics including particle size analysis, geochemistry, clay mineralogy and palaeomagnetism (Ridgway *et* *al.* 2000). Of particular importance is the study of peat deposits. When studying intercalated peats Tooley (1978) and Waller (1994) highlighted the importance of peat formation because it provides evidence of vegetational changes, which can be used to infer a reduction in water level relative to the height of the mire surface, and can act as a check on radiocarbon dating. The importance of basal peat layers has been noted (Jelgersma *et al.*, 1970; Tornqvist *et al.*, 1998; Kirby, 2000) because the sediment is less likely to have been affected by compaction and consolidation. In addition to the identification of sediment characteristics, sediments are then usually analysed for palaeobiological evidence. This is discussed further in this section and section 2.2, where many of the sea-level studies reviewed were carried out in palaeo-estuaries.

Coastal saltmarshes provide important information about sediment accumulation rates and changes in halophytic vegetation. Sediment accretion rates on saltmarshes have been used successfully to determine past water levels (Gehrels, 1999; Chmura *et al.* 2001). The most significant disadvantage of the study of saltmarshes is the problem of compaction and consolidation of sediments (Greensmith & Tucker, 1986; Allen, 1991, 2000). The study of saltmarsh vegetation does however provide one of the best records of water–level movements. Vegetation succession studies have revealed how sensitive marsh vegetation is to shifts in the water level (Rodwell, 1991). In addition the recent developments in the study of saltmarsh foraminifera (Scott & Medioli, 1978; Rijk & Troelstra, 1997; Horton, 1999; Gehrels, 2000; Gehrels *et al.*, 2001) have confirmed their usefulness in establishing past tidal levels. This is discussed again later in the chapter.

In many estuarine studies the presence of coastal features, in particular bars and barriers, can often complicate the sea-level record (Jelgersma *et al.*, 1970; Eddison, 1983; Shennan, 1986a; Jennings *et al.*, 1998). The presence or absence of such a feature can often distort the sea-level reconstruction. It is therefore important to establish whether such a feature was present and determine whether the sea-level signal suggests peat formation occurred in the shelter of the barrier (Waller, 1988) or whether it formed as the result of a marine regression.

An alternative approach is the study of isolation basins (Shennan *et al.* 1994; Long *et al.* 1999; Lloyd, 2000) and raised beaches (Sissons, 1981a). These are basins found above current mean sea level resulting from a relative sea-level fall or from a relative emergence of the land. It is possible to obtain sea-level index points from isolation basins through the collection and analysis of marine and terrestrial interfaces and palaeo-ecological data, including pollen and diatom analysis. However, in many sea-level studies it is not possible to use isolation basins as they are not present in the study area and most examples from the British Isles are from Scotland (Lloyd, 2000).

The identification of palaeo-shorelines left exposed as a result of relative sea-level fall e.g. raised beaches and wave-cut platforms (Tooley, 1978; Haslett, 1998; van Vliet-Lanoe *et al.* 2000) is a common practice. However, it is often difficult to draw conclusions without any stratigraphical data to correlate the feature with (Tooley & Shennan, 1987). Attempts have also been made to use tsunami deposits to determine past sea-levels (Goff *et al.* 2000; Smith, 2001), however since these coastal features are uncommon and restricted to emergent coastlines, their use as an indicator of sea-level change is limited.

2.1.1 Lithostratigraphic description

The accurate recording of the sediments is vital in any research as it permits tentative conclusions to be made prior to further investigations. The type of sediment recorded in the field suggests the type of depositional environment that persisted when the sediments were laid down, including whether it was terrestrial or under any marine influence, and this can provide important information about where to obtain palaeo-ecological samples.

The choice of lithostratigraphical description scheme is also an important part of the initial study, as comparisons with other studies need to be made. Several classifications exist including Avery (1972) and von Post (1946). Although they provide useful schemes, only one scheme covered all the types of sediments found in sea-level studies, the Troels-Smith classification. Troels-Smith (1955) described the physical properties, darkness, degree of humification and the composition of the sediment. Physical properties include colour, dryness, elasticity, stratification, and boundary sharpness. Humification describes the degree of decomposition of the organic material. The sediment composition may be classified as turfa, detritus, limus, argilla or grana i.e. organic or inorganic sediments. The identification of intercalated sand, silt and clay, which suggests that deposition took place under marine or brackish conditions, and peat, which can indicate deposition under freshwater, brackish or terrestrial conditions, is essential to the study of transgressive and regressive sequences. A standard method of recording such sediments is, therefore, fundamental to any research discipline and many sea-level studies have adopted the Troels-Smith classification.

The Troels-Smith scheme is the best description available for unconsolidated sediments. Thus, for the study of past relative sea-level it provides a useful tool for describing the main sediments recorded in these types of study (peat, silts, clays and sands). The scheme also has the advantage of a consistent approach. The classification allows for a greater flexibility than many other schemes, since it acknowledges that sediments can be composed of more than one element (Waller, 1994 p.19). The Troels-Smith scheme used a 5-point scale to estimate the abundance of each component. Troels-Smith (1955) also developed a diagrammatic representation of the scheme allowing stratigraphical data to be easily represented and interpreted. A summary of the Troels-Smith classification and diagrammatic representation may be found in Appendix I.

However, this descriptive tool is by no means perfect. Identification of the sediments in the field can often lead to incorrect classification, for example distinguishing between different types of peat requires knowledge about plant macrofossils. The use of the scheme is therefore a very subjective method of identifying sediments, as it requires knowledge of the components before an objective identification can be made. In order to try and overcome some of these problems the use of particle size analysis, loss on ignition and geochemical analysis to obtain further information about the sediment composition has been employed (Ridgway *et al.*, 2000).

As part of the litho-stratigraphic study it is essential to know the height of the surface of the core relative to Ordnance Datum, the national levelling reference at Newlyn, Cornwall and therefore accurate levelling is required (Tooley, 1978; Heyworth & Kidson, 1982). It is thus necessary to level in each of the boreholes relative to ordnance datum ensuring a closing error of only few centimetres. Using existing benchmarks (points of known height above OD determined by the Ordnance Survey) it is possible to obtain ground altitudes with relative accuracy (Shennan, 1982, 1986b). An equivalent known value exists in France, Nivellement Generale Francais (NGF) measured at Marseilles by Institut Geographique National, France.

Particle size analysis can also be performed on the sediments. This is usually done by digesting the sediment in 20% hydrogen peroxide and dispersing it in Calgon before analysing the sediment with a particle sizer. This type of analysis is particularly useful when trying to interpret the origin of the sediment. For example if attempting to reconstruct changes in sedimentation which are thought to have resulted from rapid relative sea-level rise, a scaling upwards in particle size can be an important indicator (Spencer *et al.*, 1998). In coastal sediments, large particle size is usually indicative of a more rapidly moving environment, for example a tidally dominated coast. Finer material is more often associated with a shallow, calm water setting. Fine silts can often signal deposition at the limit of the tide. However, a sample which exhibits a mixture of particle sizes could be indicative of sediment slumping, suggesting a more terrestrial source of sediment.

If further information about the sediment is required, such as the accumulation rate, then geochemistry can be performed. Multi-element concentrations are measured, including Mg, Al, P, K, Ca, Ti, Mn, Fe, Cr, Co, Ba, Ni, Cu, Zn, As, Rb, Sr, Y, Zr, Pb, La and Ce (Plater *et al.*, 2000). A full description of the technique has been presented by Plater *et al.*, (1998), and is therefore not discussed here. Sediment provenance can be determined by measuring the environmental magnetism. By examining the ratio of Rb/Sr and CaO/MgO the origin of the deposit can be established, i.e. whether it is terrestrial of marine. For example, this technique was effectively used in research undertaken in the Tees Estuary, north east England. The study found that the Holocene sands recorded fell at the interface of the two groups, suggesting their origin was marine (Plater *et al.*, 1998). The impact of human activity in the late-Holocene in particular was also able to be determined by using the above techniques. This highlighted the potential of geochemistry and environmental magnetism in monitoring coastal sediment changes in a period where most biostratigraphic indicators are weak. The techniques of PSA and geochemistry together could also help establish whether the last 2000 years has seen a relative rise in sea-level or whether changes in sediment flux have caused changes in the coastal configuration. This is discussed further in Chapter Four and Seven when the local controls on sea-level change are considered.

2.1.2 Biostratigraphical Evidence

Palaeoecological indicators as a method of inferring past sea-levels have been used extensively over the past fifty years (Godwin, 1962; Devoy, 1977; Long & Innes, 1993). Many of these studies used a single indicator, such as pollen, to infer past water levels. However, more recently a multi-proxy approach to Quaternary science has been adopted. This involves the use of multiple indictors, as it became apparent that a single indicator did not provide conclusive evidence and that several indicators enabled a more detailed reconstruction to be carried out. The use of pollen has continued to be one of the most commonly used methods of inferring past sea-levels but alternative indicators for example diatoms, foraminifera, mollusca, ostracoda, chironomidae and testate amoebae have been successfully used. These "natural archives" (Matthews, 1996 p.3) provide essential ecological information. Each species occupies a distinct habitat, which allows conditions such as salinity, temperature and pH at the time of sediment deposition to be estimated.

Using the theory of uniformitarianism, modern day analogues have been developed which provide information about the habitats that species occupy today. Assuming environmental variables have remained the same, past conditions can be determined. In addition to this theory, transfer functions, variants on multiple linear regression models, have been developed. Transfer functions allow quantitative relationships between biological data and a set of environmental variables to be established. Once this relationship has been determined for modern day situations, multivariate numerical analyses allow the function to be applied to the fossil assemblage (Birks and Birks, 1980). The transfer function employed in this study will be discussed later in this section.

Pollen Analysis

The use of pollen as a method of reconstructing past Quaternary environments has been used reliably over the past century. Von Post (1924) published the pioneering paper suggesting the use of pollen to reconstruct past environments by studying the presence of fossil pollen grains, preserved in organic sediments. The main advantages of pollen analysis are that pollen grains are produced in great abundance, the majority of which never fulfil their reproductive function and fall to the ground. Most of these rapidly decay unless preserved in poorly oxidised places. Before reaching the ground the pollen is well mixed by the air resulting in a uniform pollen rain. This pollen rain is a function of the composition of the parent vegetation (Birks & Birks, 1980).

Pollen can also act as an approximate indicator of the age of sediments, where comparative dated sequences exist, and can be used to provide tentative estimates to verify radiometric dating (Birks & Birks, 1980). The principles of pollen analysis including the preparation of sediments, the morphology of the pollen grains and the calculation and presentation of pollen data are well documented in Birks & Birks (1980) and are therefore not discussed in detail here.

Fossil pollen is well preserved in many estuarine sedimentary environments, including some non-oxidised environments. Modern taxonomy of pollen is well known and the identification of fossil pollen thus provides a useful tool for reconstructing past climates, sea-levels and land use. Only a very small amount of sediment is required, as pollen grains are small (most are less than 40 μm) and occur in abundance throughout organic units. However, the technique if not without its weaknesses, the most significant being the problem of dispersion which can often lead to sources of error in interpretation, for example *Pinus* pollen tends to be transported long distances. A second problem is that of damage to the pollen grains during the laboratory preparation. In an attempt to combat this, and in order to calculate the concentration of pollen grains, marker grains may be added to the sample at a known concentration.

The use of pollen analysis as an indicator of past vegetation can be used in sea-level studies to describe changes from freshwater to halophytic plants. Pollen analysis has been used in this way in the study of saltmarsh taxa, as a tool for inferring changes in tidal level (Godwin, 1962; Morzadec-Kerfourn, 1969; Tooley, 1978; Devoy, 1979, Waller, 1994; Metcalfe, 2000). Although these studies did attempt to reconstruct the sea-level history of individual sites (Kent, Normandy, France, the Thames, East Anglia and the Humber Estuary) conclusions based upon vegetation history alone provide insufficient and often misleading information (Birks & Birks, 1980). A useful summary was presented by Waller (1994) based upon work undertaken in the Fens.

Environment	Indicators
Marine/Brackish water/unvegetated	Pollen: regional, coastal, over-represented buoyant grains (*Pinus, Pteridum*) and secondary pollen (pre-Quaternary spores). Diatoms present. Clastic sediments
Saltmarsh	Pollen: Gramineae, Chenopodiaceae, *Artemesia, Plantago maritima*. Transition from clastic/organic sediments
Reed swamp	Gramineae, *Typha, Phragmites*. Transition from clastic/organic or organic sediments
Sedge Fen	Herbaceous pollen and macrofossils. Organic sediments
Fen carr	*Alnus* and *Salix* dominate. Organic sediments
Fen woodland	*Alnus* and *Quercus* dominate. Organic sediments
Dry land	Woodland: *Tilia, Quercus, Corylus* Open: Gramineae and herbs. Buried soil horizons.
Poor fen	*Betula, Sphagnum* spores. Organic sediments
Bog	*Sphagnum* spores, *Calluna* pollen. Organic sediments
Open freshwater	Aquatics and floating macrophytes. Shell marl/limnic sediments

Table 2.1 Pollen as a tool for reconstructing past coastal environments

After: Waller (1994)

Diatom Analysis

Diatoms are unicellular, eukaryotic, micro-organisms (Round *et al.;* 1990). The silica shell that surrounds the organism possesses distinct characteristics (shape, size and surface patterning), which makes their identification and habitat inferences possible. The preservation of the diatom valves also highlights their importance as a tool for reconstructing past environments, in particular in coastal areas (Denys & de Wolf, 1999). Vos and de Wolf (1988, 1993) identified the potential of using diatoms in tidal environments for reconstructing coastal wetlands, and thus sea-level changes. Diatoms have also been widely used to observed changes in lake sedimentation (Battarbee, 1979; Mannion, 1986 a/b). These fossil algae provide essential information about the depositional environment of minerogenic sediments and allow conclusions to be drawn about the type of marine or estuarine environment.

Palmer & Abbott (1986) identified the main attributes of diatoms as being firstly; diatoms are widespread in natural aquatic environments. Secondly, many species prefer specific salinity conditions. Thirdly, the silica constituting the valves is relatively resistant to chemical alterations after burial and finally that diatoms are often preserved with radiometrically dateable carbonaceous material.

Diatoms may be classified according to the environmental information required; the classes may be divided into life-form, salinity, pH spectrum, nutrient content spectrum, temperature, tides and current (Vos and de Wolf, 1993) and more recently tidal altitude (Zong, 1998). Life form includes divisions into plankton, freely floating on surface waters; tychoplankton, those washed-in from other communities; epiphytes, those attached to plants; benthos, taxa attached to solid surfaces; epipelon, species living on mud surfaces; and benthos episammon, those attached to sand grains. Vos and de Wolf (1993) also distinguished between autochthonous and allochthonous diatoms. Autochthonous diatoms lived at the place of deposition whereas allochthonous diatoms have been washed-in. The salinity classification (Table 2.2) is divided into polyhalabous, mesohalabous, oligohalabous, halophabous and euryhaline (Husdedt, 1957).

Assemblage	Salinity tolerance	Environment
Polyhalabous	> 30 %	Marine
Mesohalabous	0.2 – 30 %	Brackish
Oligohalabous	< 0.2 %	Freshwater
Halophabous	0	
Euryhaline	Highly tolerant	

Table 2.2 Diatom salinity classification

After Hustedt (1957) In: Lowe & Walker (1984)

Fig. 2.1 shows these divisions and their environmental habitat (after Carter 1992 p: 121). The main advantage of diatoms as indicators of sea-level is that distinct habitats can be identified from the saline environments that diatom species inhabit. Environments may be divided into freshwater, brackish and marine environments, and this can now be quantified in terms of position within the tidal range (Zong, 1998)

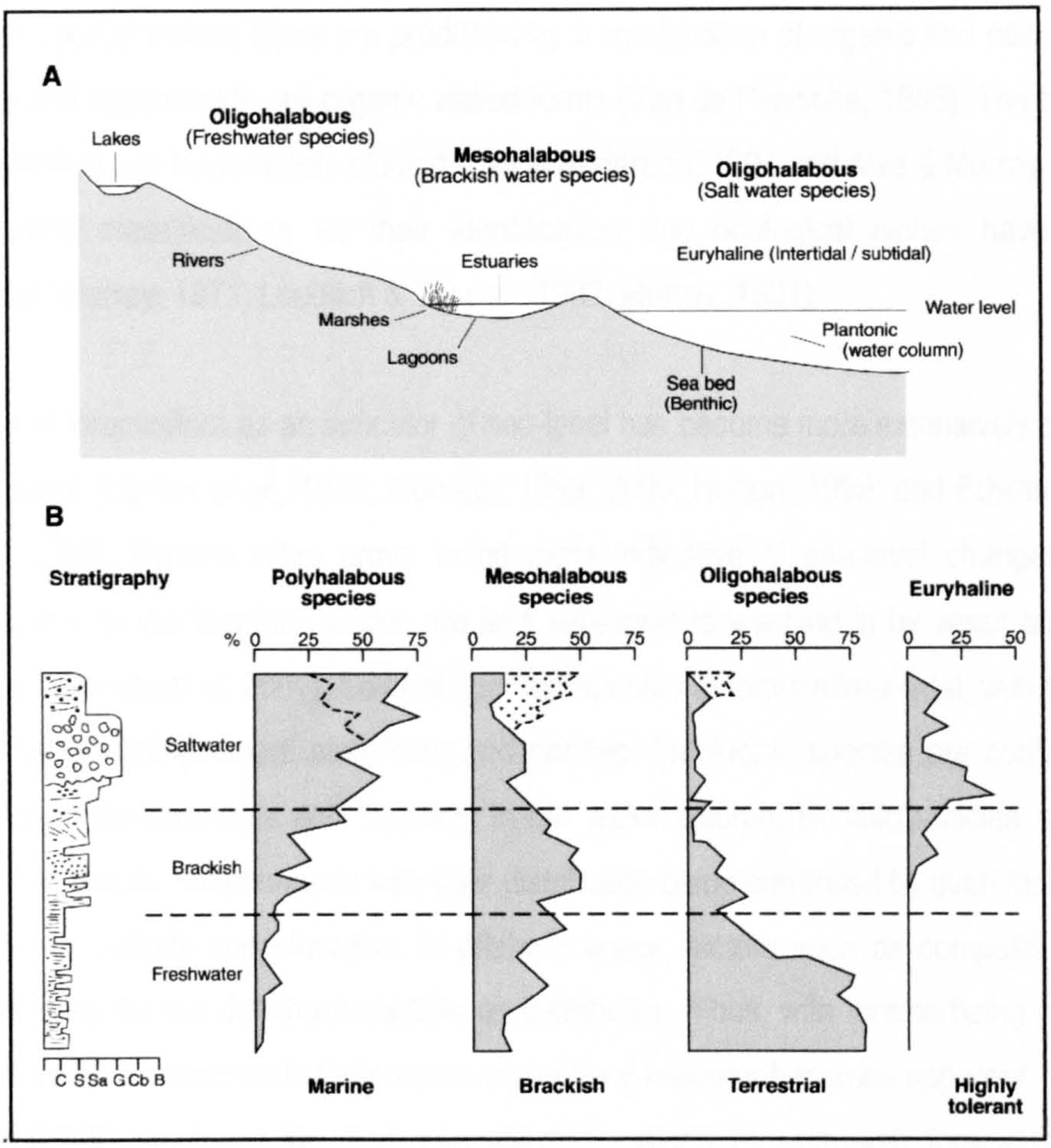

Fig. 2.1 Diatom classification and habitat (Carter, 1992)

However, several disadvantages also exist. Firstly the problem of dissolution (Ryves *et al.* 2001) exists. Certain diatoms species are more susceptible to dissolution than others and this must be taken into account when interpreting diatom counts. Diatoms are also very susceptible to washing-in and fossil valves are often found outside of their normal ecological boundaries, for example the species *Paralia sulcata*, a marine diatom, is found in high abundance in brackish areas and is often washed-in along channels that have developed in marshes. As studies of modern sites and the development of transfer functions (Zong & Horton, 1999) becomes more widespread these problems should become easier to overcome.

Foraminiferal Analysis

Foraminifera are unicellular testate marine organisms. Four basic shell types have been identified; calcareous types are formed by secretion by the organism; agglutinated/arenaceous types are made of foreign particles cemented together by the organism; porcelaneous types are produced by a combination of organic and calcareous material and agglomorids are organic walled forms (Van de Plassche, 1986). The biology of foraminifera has been widely studied (Lee & Anderson, 1991 and Alve & Murray, 1995) and several classifications for their identification and ecological niches have been published (Murray, 1971; Loeblich & Tappen, 1982; Murray, 1991).

The use of foraminifera as an indicator of sea-level has become more extensively used in recent years (Horton *et al.,* 1999; Gehrels, 1999, 2000; Horton, 1999; and Edwards and Horton, 2000). Forams often prove to be more indicative of sea-level changes than diatoms, due to the fact that forams are less subjected to washing-in by water and tidal changes (Gehrels *et al.* 2001). Several hundred species of foraminifera exist, with two life modes being distinguished: planktonic and benthic. Planktonic species are confined to deep ocean environments and live only in the water column. Benthic species may be found in all marine environments with their distribution being controlled by such factors as temperature, salinity and elevation. In offshore areas, factors such as competition and predation may be the dominant controls on distribution. Thus, with forams being present in most marine environments their use as a sea-level indicator becomes apparent. Scott & Medioli (1980) produced the first comprehensive study of saltmarsh foraminifera by grouping species according to vertical depth at Chezzetcook, Nova Scotia, thus enabling tidal level to be determined. Certain species were found to be associated with particular coastal habitats and the most commonly recorded species have been used to develop transfer functions (see section 2.1.3).

Research into the distribution of foraminifera relative to altitude has allowed detailed information about the ecological habitats of particular species to be determined (see Fig. 2.2 and Table 2.3). For example, the species *Jadammina macrescens* and *Trochammina inflata* are known to inhabit middle and high marsh environments. The species *Miliammina fusca,* however is recorded on middle and low marsh settings (Haslett *et al.* 1998; Horton, 1999), thus allowing detailed information about past tidal levels to be established.

Floral zone	Foraminifera	Tidal height
High marsh	*Jadammina macrescens*	HAT
	Trochammina inflata	
Middle marsh	*Miliammina fusca*	MHWS
Low marsh	*Jadammina macrescens*	
	Miliammina fusca	
Mudflat	*Elphidium williamsoni*	MHWN
	Haynesina germanica	
	Quincquelochulina spp.	MTL

Table 2.3 Foraminiferal assemblage zones (After: Horton, 1999)

However, there are also some limitations associated with the use of foraminifera in sea-level studies. Firstly, a shortage of contemporary data sets limits their application. Until recently few studies of the fossil foraminifera of the UK had been undertaken with Scott (1978) and Culver & Banner (1978) being the earliest papers written. Recent studies (Haslett, 1997; Horton, 1999; Gehrels, 2000; Horton *et al.* 2000) have been attempting to fill the gaps in the data sets and data are gradually becoming more widely available.

Other biological indicators of sea-level change

In addition to the techniques described in detail above several methods exist, which may be used to determine past sea-levels. Firstly, ostracoda are defined as "tiny crustaceans which characteristically posses a bivalved, calcareous shell." (Van de Plassche, 1986). Ostracod density and diversity are particularly sensitive to changes in water depth, making them a useful sea-level indicator. Ostracoda are found in most aquatic environments (freshwater and marine) and exist under a wide range of temperature and salinity conditions, allowing them to be divided into freshwater, brackish water and marine groups. The relationship between salinity and ostracod distribution has also been widely reported (Knox & Gordon, 1999; Friedman & Lundin, 2001; Knox, 2001). Van Harten (1986) described bathymetric distribution as being one of their main attributes. Comparisons between the depth ranges of recent ostracod species and palaeo-depths have been well documented in the Gulf of Mexico (Van Morkhoven, 1963; Pokorny, 1971). Although, ostracoda provide similar information to that provided by foraminifera and diatoms, at present no reliable transfer functions for ostracoda exist, thus their use in sea-level reconstruction is still limited.

Secondly, mollusca may be used to determine past sea-levels. Mollusca are divided into four ecological groups; the slum group, which occupy poor water bodies, the moving-water group which inhabit freshwater streams and ponds; the ditch group found in slow moving water ditches, and the catholic group which inhabit any water body except the slums. However, it is the marine mollusca that are most useful to the study of sea-level change. They occupy a wide range of habitats from the inter-tidal zone to deep offshore waters. The mollusca may be infaunal, that is burrowing, or epifaunal, attached to surfaces or other organisms. Their distribution and species diversity are related to several controls, including salinity (Bernard, 1983), temperature (Feyling-Hanssen, 1955), food supply, oxygen level, nutrient availability, light, shelter and competition. In shallow or enclosed seas it is believed that salinity is the dominant control, making them a useful indicator of sea-level change. Peacock (1993) produced a study of the relationship between species, temperature, salinity and depth using existing published data. The depth range is shown to be a function of "temperature, salinity, bottom conditions, shelter and food supply" (p.272). However, one problem highlighted was that the depth range was large which can lead to problems when trying to interpret the palaeoenvironment of species. Despite these differences Peacock (1993) did provide invaluable information about salinity tolerances and depth ranges of specific species.

Thirdly, testate amoebae (thecamoebians) are a group of freshwater foraminifera, which allow hydrological variations to be well documented especially in peat deposits. Charman *et al.* (1998) showed that testate amoebae and diatoms showed similar distribution patterns when based upon salinity classification, thus revealing their potential as a sea-level indicator. When compared with the foraminifera data it may be seen that testate amoebae offer information at altitudes where foraminifera were not recorded, although again the poly- and meso-halobian diatoms groups can provide this information. Charman *et al.* (1998) used testate amoebae in conjunction with foraminifera and diatoms to study sea-level change in the Taf Estuary, South Wales. The study made a direct comparison between diatoms, salinity and foraminifera revealing strong relationships (refer to Fig. 2.2). For example most testate amoebae were confined to the samples occupied by the oligohalabous range of diatom species. By distinguishing groups similar to the diatom groups, according to salinity, the potential of using testate amoebae as a sea-level indicator was highlighted. Charman & Hendon (2001) have since added considerably to the information available. There is still much information missing and to date few transfer functions have yet been published. However, it must be noted that their preservation in organic sediments has an advantage over the foraminifera and diatoms, which do not tend to preserve well.

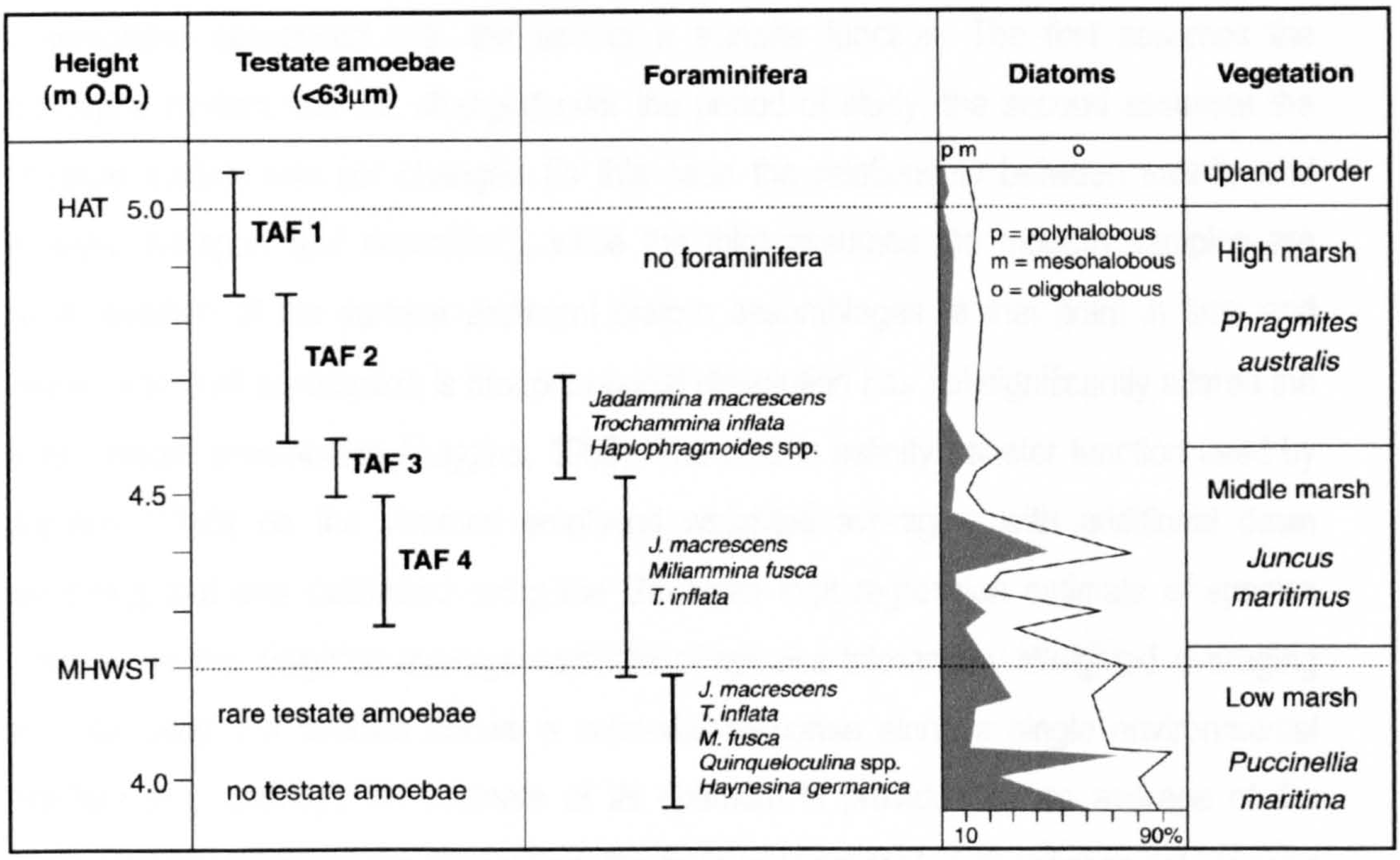

Fig. 2.2 Comparison of testate amoebae, diatom, foraminifera and vegetation data zoned according to altitude from the Taf Estuary (Charman *et al.* 1998)

2.1.3 Transfer functions

Transfer functions are based upon variants upon multiple linear regression models. The transfer function allows a quantitative relationship between biological data and environmental variables to be established. The approach assumes that an assemblage of organisms is related to the environment by a complex function (the transfer function) and once this relationship has been determined for modern situations, multivariate numerical analyses allow the function to be applied to the fossil assemblage (Birks and Birks, 1980).

Juggins (1988) produced a salinity transfer function for diatoms based upon the following theory. The basic method of identifying the relationship between a set of biological responses and environmental variables uses the equation

$$E_m = X_m T_m$$

where X_m is a matrix of biological responses (in this case the proportion of each diatom taxa), E_m is a matrix of environmental variables (in this case salinity) and T_m is a matrix of modern transfer functions (Juggins, 1988). When attempting to establish the fossil assemblage, E_m and X_m are replaced with E_f and X_f respectively. There are several assumptions associated with the use of a transfer function. The first assumes the ecological system has not changed over the period of study, the second assumes the physical system has not changed (in this case the relationship between salinity and erosion, transport and deposition), while the third assumes the modern samples are representative of the surface sediment diatom assemblages at that point in time and space. The final assumption is that post-burial dissolution has not significantly altered the fossil diatom assemblage (Juggins, 1988). The diatom salinity transfer function used by Juggins (1988) on the Thames employed weighted averaging with additional down weighting and was calibrated using the Gaussian logit regression estimate of species optima and the weighted average estimate of species tolerances. Weighted averaging may be used if a species shows a unimodal response along a single environmental gradient (e.g. salinity), an estimate of its optimum is provided by an average of the environmental values at the sites where the species is present. If abundance data is used then values can be weighted according to abundance at a site:

$$U_{wa} = \sum_{i=1}^{n} YiXi / Y_{+}$$

where Yi is the abundance of the species at sites I, Xi s the value of the environmental value at site I and Y_+ is the species total and n is the number of sites

Juggins (1988) supported the salinity classification published by Hustedt (1957) and Simonsen (1962), but concluded that the palaeosalinity classification could be improved. Juggins also concluded that both the life and death assemblages suggest that the majority of diatom taxa in the surface sediments were derived from habitats within the estuary, excluding *Raphoneis amphiceros, Raphoneis minutissima* and *Paralia sulcata*, which were thought to have been washed-in, again highlighting the problem of species being washed-in. The transfer function developed by Juggins (1988) has allowed sea-level research to develop, providing such information as past salinity levels and tidal levels. Diatom-based tidal-level transfer functions can now be used to reconstruct sea-level movements (Zong & Horton, 1999). Using a weighted average (the transfer function), precise relationships between diatom distribution and tidal levels may be established.

More recently, Zong & Horton (1998) carried out an extensive study of modern sites using six environmental variables; ground altitude, relative abundance of each floral species and total cover; sand fraction; silt fraction; clay fraction and organic matter. CCA (canonical correspondence analysis) was used to relate species data with environmental and ecological data. The transfer functions show clear zonations in species distribution dividing habitats into upland, high marsh, middle marsh, low marsh, muddy tidal flats and sandy tidal flats.

Horton (1999) stated that the controlling variables in determining past sea-level could only be numerically achieved through the construction of transfer functions. Thus, with forams being present in most marine environments their use as a sea-level indicator becomes apparent.

The use of a foram-based transfer functions in the reconstruction of past sea-levels has proved to be useful, however, certain limitations have been encountered. Edwards (1998) found that the transfer function was only reliable for reconstructing Standardised Water Level Indices (SWLI) between 130 and 220, where MHWST is 300. A second limitation found by Edwards (1998) was that when obtaining modern day samples, foraminiferal distributions appeared to be strongly affected by other controls such as sediment composition and that altitude was just one factor.

The implications of using transfer functions in sea-level studies have been examined by Horton *et al.* (2000). The study compared the differences between the indicative meanings found when using the traditional lithological based approach (LBA) and the foraminiferal-based transfer function (FBTF). A variety of sediments were studied including intercalated peats, basal peats and clastic sediments concluding that on average the indicative meaning of transgressive index points were 0.19 ± 0.12m higher when based on the FBTF than when applying the LBA. However, it was proposed that this was due either to the rapid response time of foraminiferal assemblages compared with lithological indicators or that the contemporary foraminiferal data set is too spatially uneven and thus more habitat information is required.

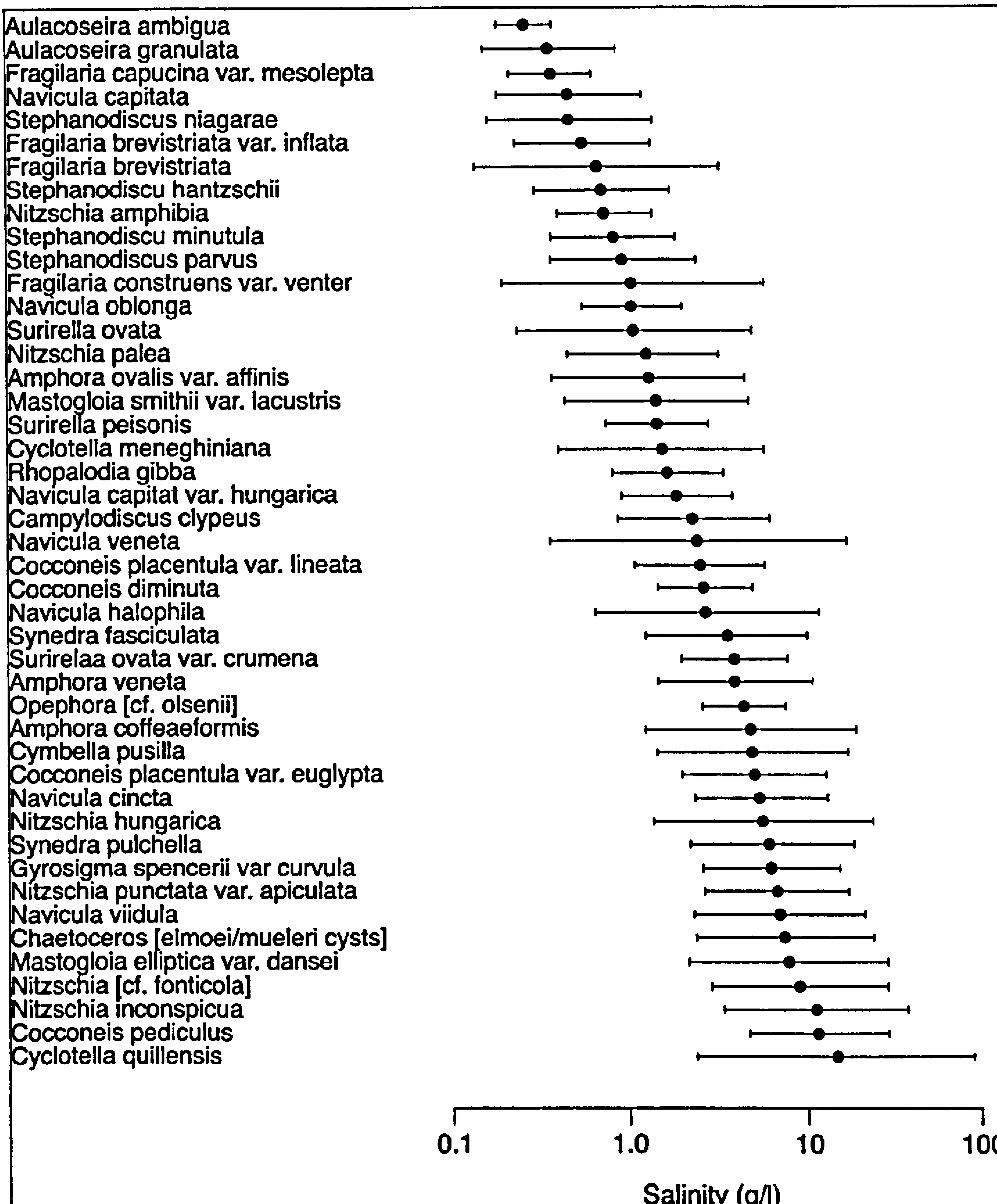

Fig. 2.3 Diatom salinity ranges for various diatom species showing the salinity range tolerances of some of the more commonly recorded diatom species. The graph shows the range of salinity levels (in grams per litre) that the species will inhabit. (University College London *pers. comm.*)

It can therefore be seen from the above discussion that many biostratigraphic techniques are available when attempting to reconstruct past sea-level. Although each indicator provides useful information about the controlling environmental variables, it can be seen that no single method provides a complete understanding. Therefore, the use of a multi-proxy approach can allow the limitations of each indicator to be overcome, thus providing a more complete interpretation of sea-level change.

2.1.4 Dating techniques

Radiocarbon dating

The above techniques for interpreting past environments can only provide information about what events took place, they cannot assign a time frame, except for pollen which can be assigned a regional pollen assemblage zone as a rough chronozone of time (Tooley, 1978). It is essential in a study of past sea-levels to be able to date an event. The main methods of dating past sea-level events may be grouped under the term radiometric dating. Radiocarbon dating was first used in 1947 and subsequently all dates are now denoted in years BP, where present is AD1950. Radiometric dating relies upon the principle of isotopic variation in content due to radioactive decay. The content of an isotope within a material will decrease by a known factor per unit time, the half-life of an isotope. It is possible to use several isotopes in this way, ^{14}C, ^{238}U, ^{235}U, ^{210}Pb and ^{40}K, however, for an accurate date to be obtained the isotope must possess the following attributes. The isotope must occur in measurable amounts and must be distinguishable from other isotopes. Secondly, its half-life must be appropriate to the period being dated and finally the initial concentration level must be known and there must be a connection between the event being dated and the start of the decay process (Olsson, 1986). The procedure used on the samples and the calibration of the results from this research is described in Chapter Three.

Accelerated mass spectrometry (AMS) dating is the most widely used method of absolute dating employed in sea-level studies. The decreasing ^{14}C content within sediments provide a measure of the age of the sediment. The advantages of this method are that it may be performed on a wide range of sediments including peat, wood, bone, shells and marine and lacustrine sediments. A second advantage is that only a small amount of material is required, as little as 0.2 mg, with an ideal sample size of 5mg (Pilcher, 1991). The use of accelerators allows dates to be obtained for very small samples, which is essential when using such materials as shell and bone (Berglund, 1986). This method has been very useful to past sea-level studies.

More recently work has been carried out in an attempt to obtain AMS radiocarbon dates from foraminifera tests (Horton *et al.* 2000). Results were compared with conventional AMS dates obtained from the gastropod *Hydrobia ulvae*. The age ranges produced an overlap of $\pm$ 2 σ (standard deviation) and therefore Horton *et al.* (2000) concluded that "... AMS dating of calcareous foraminifera from inter-tidal sediment is a viable addition to the traditional use of transgressive/regressive contacts in sea-level chronologies" (Horton *et al.*, 2000: p.49).

However, as with all dating techniques the accuracy and precision of the date is often in doubt. All radiocarbon dates are given as a figure plus or minus the standard deviation, thus giving a probability that the date lies within a range. For example a date of 5000 $\pm$ 100 years BP will mean that there is a 68% probability that the age is between 4900 and 5100 years BP. Radiocarbon dating in sea-level studies tends to rely upon the contacts between peats and clays. Heyworth & Kidson (1982) stated that modern carbon contamination is less of a problem in sea-level studies, however the issue of penetration by younger roots and other stratigraphical disturbances will introduce additional errors. Heyworth & Kidson (1982) concluded by stating "a far greater allowance must be made for uncertainties in radiocarbon results than the usual $\pm$ one standard deviation" (p.100) by ensuring samples remain uncontaminated and that results are presented with all error bands attached. A second disadvantage of ^{14}C dating is contamination by old carbon, which can often give older dates. 1% contamination can make the date 80 years older (Pilcher, 1991). Contamination by modern carbon has also posed the problem of making the sample appear younger than it actually is. Some freshwater molluscs take up carbon from water, which contains bicarbonate, which can distort results. Finally, variations in the production of ^{14}C in oceans and in the atmosphere can cause inaccuracy. The principle relies upon the assumption that levels have remained constant through time. It is known that this assumption is invalid. To avoid these problems, dates are therefore cited in calibrated years (Stuiver *et al.*, 1998). This allows a minimum and maximum age to be assigned, according to the range as determined by Stuiver *et al.*, (1998). Calibration is usually performed using the Calib programme (Stuiver & Reimer, 2000).

Luminescence dating

A second dating technique available to sea-level studies is the use of luminescence dating, thermoluminescence (TL) and optically stimulated luminescence (OSL). The accumulation of metastable electrons resulting from the bombardment by alpha, beta and gamma particles accumulates over time (Smart & Frances, 1991). Heating permits these electrons to be released and under controlled conditions the light emitted from the sediment is known to be proportional to the number of electrons stored in the crystal lattice. The age equation is

$$\text{Luminescence age} = \frac{P - D\cos}{\dot{D}\alpha\beta\gamma}$$

where *P* = the palaeodose, *D* αβγ = effective annual dose due to U, Th and K.

After: Bailiff & Tooley (2000)

The method of luminescence dating may also be applied to date archaeological objects such as pottery and flints and to sediments which contain quartz and feldspar. However, several errors exist within this method. First, it is not possible to achieve a precision of better than ± 5 % (at the 68% confidence level) due to the calibration techniques used within the laboratory. Secondly, decay of uranium is not uniform, thus one of the underlying assumptions is again invalid. Thirdly, the water content of the sediment will affect the result. Finally, radioelements are known to migrate through the sediment, thus calculating an annual dose is often difficult.

Bailiff & Tooley (2000) compared luminescence dates with radiocarbon dates finding that for intercalated peats the overlap was within the 2 standard deviation limit. On clastic sediments it was concluded that the possibility that luminescence ages are younger than the true ages must be taken into consideration. Further work relating to the annual dose is required and "in particular the extent of radioactive disequilibrium and the assumptions made concerning water content history" (Bailiff & Tooley, 2000: p.66).

The type of dating technique employed depends entirely upon the type of sediment and the age range under consideration. In Holocene sea-level studies radiocarbon dating (often AMS) has proved to be most beneficial since it is often practical to obtain dates from small amounts of material e.g. shells or wood fragments. However, because dates can only be obtained from organic sediments, the sea-level changes that are evident in inorganic samples can not be dated, presenting a major limitation. The accuracy of radiocarbon dates for the period under consideration however poses many problems. All radiocarbon dates are cited with an error, which is typically less than 100 years. When studying a short period (such as the late Holocene) this can mean that dates are not accurate enough to detect minor changes such as century-scale sea-level oscillations. However, it remains the best method currently available for the materials involved.

2.1.5 Sea-level index points and the construction of sea-level curves

A sea-level index point (SLIP) is a point for which altitude, age, the indicative meaning and range and the sea-level tendency are known (Shennan *et al.* 1994). Indicative meaning refers to the tidal level that is associated with the SLIP, usually Mean High Water Spring Tide or Highest Astronomical Tide and range allows for any uncertainty (Shennan, 1986b; Haslett, 1997). Sea-level tendency refers to whether the SLIP represents a marine transgression or regression. Each point represents a sea-level tendency but in order for a complete history of sea-level change within an estuary to be known, a series of sea-level index points is required. Tooley (1978) and Devoy (1987) both recommended that SLIP's should be drawn from small, clearly definable areas. There should be a clear understanding of the palaeogeography. Those used in the construction of sea-level curves should come from the same type and represent the same palaeoenvironment and have the same indicative meaning. Lastly, radiocarbon dating should be verified by other dating methods.

Once a series of sea-level index points has been obtained for one area, age-altitude plots may be created. The index points are plotted with error boxes, which represent 2 standard deviations ($\pm 2\ \sigma$) of the radiocarbon date and a vertical error bar showing the direction and extent of the sea-level movement. In addition, a relative sea-level curve may be constructed which shows the pattern in sea-level trends over a period for a region. The histogram approach, or tendency approach, allows periods of transgressive and regressive movements to be plotted, and the rate of tendency to be observed. However, it does not allow the construction of a sea-level curve to observe the general pattern of change. Fig. 2.4 shows examples of the two types of graph.

2.1.6 Geophysically modelled data

Modelling sea-level changes

In an attempt to estimate sea-level variations geophysical models have been developed, with leading models being developed by Mörner (1987), Lambeck and Nekada (1990), Lambeck (1990a,b, 1995, 1997), Lambeck *et al.* (1990) and Peltier (1990). Lambeck based his model upon research on the Fennoscandian ice sheet and used ice models to construct the response of the Earth to deglaciation. Lambeck (1990) noted that the Late Pleistocene and Holocene sea-level changes exhibited a considerable variation, both temporally and spatially, when compared to the present-day rate of sea-level change. He attributed this to variations in ocean volume resulting from ice sheet melting, crustal response to changes in ice load and tectonic movement of shorelines. He identified the major source of the post-glacial sea-level rise to be from Antarctica and the Barents and Kara ice sheets, suggested that present-day secular sea-level rise has a global average of 1.2 mm/yr, and that nearly half of this may be attributed to the melting of mountain glaciers and a small contribution by the Antarctic ice sheet, with the remainder being the thermal expansion of the upper 100-200m of the ocean column. The study did not attempt to provide a model of sea-level change but concluded that "the modelling of sea-level change requires further development...detailed descriptions of coastlines are required in order to model the loading effect of meltwater with precision ... improved rheological descriptions of the Earth are required." (p.216)

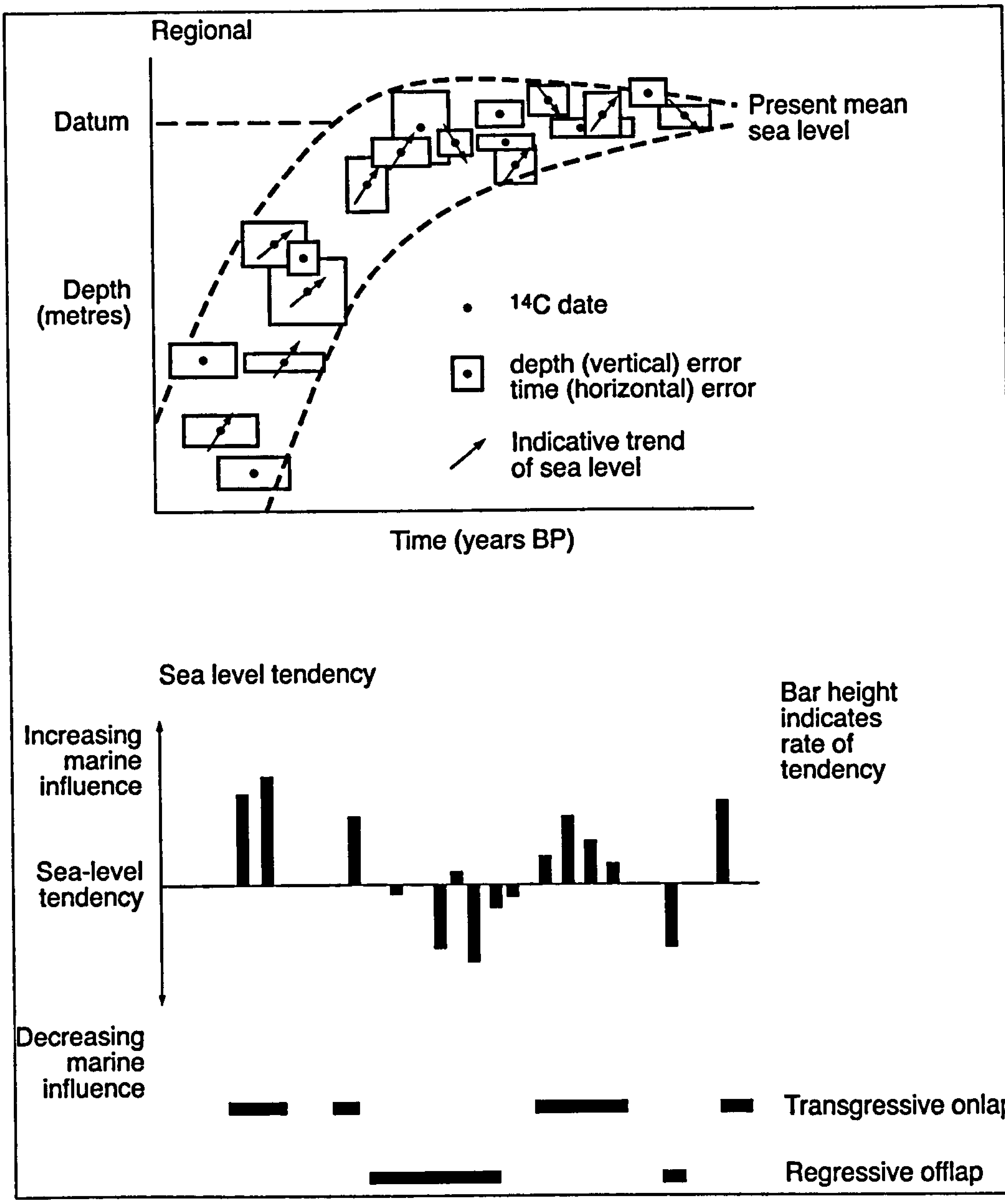

Fig. 2.4 Plots of sea-level index points a) showing errors b) relative sea-level changes (tendency approach). After Carter (1992)

Lambeck *et al.* (1990) produced a numerical model for north west Europe. The model estimated that the contribution of the Fennoscandian ice sheet to post-glacial global sea-level rise was 1-2 to 13-14m. The model relies upon the underlying principle of an inversion of the observed sea-level measures taken from the Fennoscandian ice sheet. The research again suggested that a major cause of the rise in sea-level was the melting of the Barents-Kara ice sheet. He argued that the variations in sea-level change are due to several constraining factors. These constraining mantle parameters were; upper mantle viscosity at 3–5 x 10^{20} Pa s; lower mantle viscosity at 2–7 x 10^{21} Pa s; and lithospheric thickness as 100–150 km. Mantle viscosity is important as it allows convection to be quantified. The research presented several mathematical formulae to develop the sea-level change model.

The equation to resolve the positions of former shorelines using latitude φ, longitude λ at times t relative to the present shore line at time t_0 is

$$\Delta\zeta(\varphi, \lambda : t) = \zeta(\varphi, \lambda : t) - \zeta(\varphi, \lambda : t_0)$$

where ζ is the level at any time t relative to some arbitrary crustal reference point. The sum of these can be expressed to solve sea-level change in the absence of vertical tectonics.

$$\zeta(\varphi, \lambda : t) = \zeta_r(\varphi, \lambda : t) + \zeta_i(\varphi, \lambda : t) + \zeta_w(\varphi, \lambda : t)$$

and the relative change as

$$\Delta\zeta(\varphi, \lambda : t) = \Delta\zeta_r(\varphi, \lambda : t) + \Delta\zeta_i(\varphi, \lambda : t) + \Delta\zeta_w(\varphi, \lambda : t)$$

It may be seen from the equation above that the model contains three components; the rigid body term ζ_r, the ice unloading term ζ_i and the water loading term ζ_w. The first term assumes ice melt on a rigid earth and includes the gravitational attraction of the ice and water. The equation is a function of the time and space history of the ice load I(t) and of the geometry of the oceans O(t) into which the meltwater is being added. The second term relates to the change in sea-level produced by the deformation of the Earth in response to glacial unloading and is a function of the Earth's rheology and ice load I(t). The third term is any additional deformation produced by the loading of glacial meltwater distributed into the oceans and is a function of η, of the ocean geometry O(t) and of sea-level change itself ζ(t). Relative sea-level is expressed as

$$\Delta\zeta = \sum_{n=0}^{N} \Delta\,\zeta(n) = \sum_{n=0}^{N} [\,\Delta\zeta_r^{(n)} + \Delta\zeta_i^{(n)} + \Delta\zeta_w^{(n)}]$$

where N = 180 (in the paper) which is a function of the site location and the Earth's response function.

Lambeck *et al.* (1990) also provided several sea-level curves based on observational evidence including several for the British Isles and north west Europe (see Fig. 2.5). The pattern of predicted sea-level change agrees well with the observational data, however, for most sites the model over- or under-predicts the values. The Earth parameters are predicted well by the models and the research concluded that "the present model predicts qualitatively ... but is inadequate for accurate quantitative modelling purposes. Further observational evidence is also required." (Lambeck, Johnston & Nekada, 1990: p 467) Comparisons were made to observed sea-level curves and three sites; Firth of Forth, Scotland; Groningen, Netherlands and Elbe Estuary and Eider River, West Germany, there is a "reasonable agreement between theory and observation is obtained for model 2 for which $H_l \cong 100$ km" (p465). The study concluded that further improvements were needed to improve the spatial and temporal resolution of the model.

In 1995, Lambeck continued his work to include more on the British Isles. The paper published sea-level curves, observed and predicted for nine UK sites. The model permits predictions of palaeobathymetry and palaeoshorelines for the Britsh Isles, including the North Sea. The Holocene history of sea-level change is proposed, which dates the maximum sea-level attained around the British Isles and the North Sea to be 6000 years BP. The authors found "the predicted amplitudes are also consistent with the observations (keeping in mind that the predictions are for mean sea-level and not the shoreline formation level)" (p447). Lambeck acknowledged constraints within the model and put forward the notion that the deglaciation of the British ice sheet differed from other major ice sheets. The paper concluded that examination of more elevated isolation events is required, as well as the study of presently submerged depressions that were once above sea-level.

Lambeck (1997) extended his studies further to include the French Atlantic and Channel coasts by estimating the effect of isostatic rebound and the addition of meltwater to produce reconstructed sea-levels along the coast. He emphasised that combining sea-level curves into a single curve along a coastline was not acceptable and that it is necessary to produce individual curves for small sections of the coast. Lambeck produced curves for Pas-de-Calais and Picardie, Normandie, Côtes-du-Nord, Finnistère, or the Vendeé and Charante-Maritime.

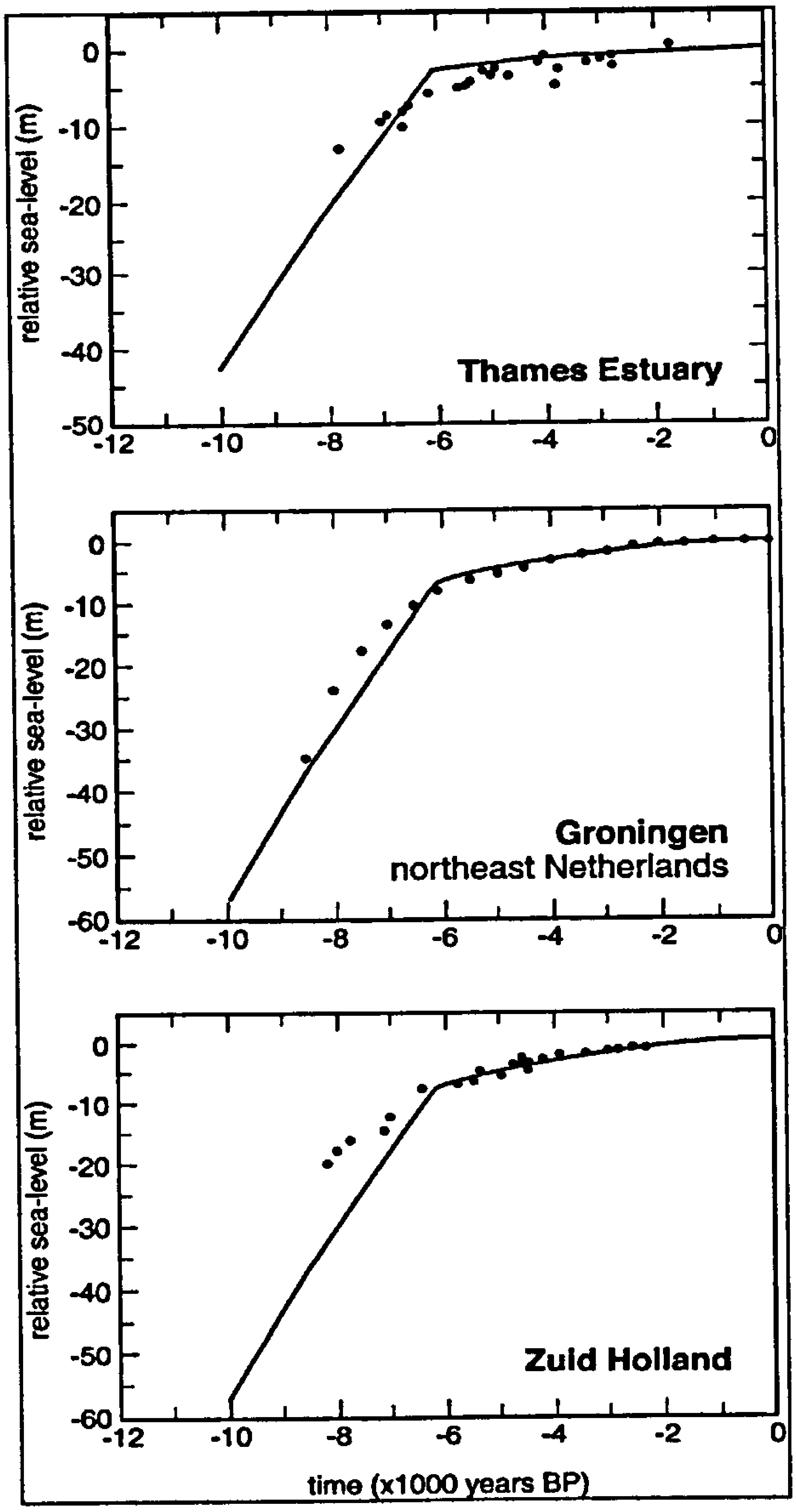

Fig. 2.5 Examples of sea-level curves for Britain and NW Europe showing observed data (•) versus predicted data (—) Lambeck (1990)

In 1998, Lambeck studied the glaciation and sea-level change for Ireland and the Irish Sea using both predicted values and observed rates of sea-level since the Late Devensian/Midlandian period. Model predictions were found to exceed observed values for the sites studied. In particular, the predicted mid-Holocene high stand values far exceeded the actual observed values. The paper concluded "the model predictions do point to areas where improved observational constraints are most desirable if a full understanding of the ice-sea-earth interactions is sought and if the full implications for these interactions of palaeogeographic and palaeo-environmental reconstructions are to be understood" (Lambeck, 1998 p.871).

It may be seen from the research cited above that although Lambeck's model predicted the isostatic response of the Earth reasonably well, the timing and rates of sea-level change did not correspond well with observed data. A general similarity in the overall pattern of sea-level change can often be seen (Lambeck, 1997) but observed values do not agree with predicted rates. The quantitative element of the model prediction can only be improved by increasing the amount of observational data that is available to be compared with the modelled data.

In addition to the work of Lambeck, Mörner (1976, 1980) also developed a high-dynamic gravity model stating that any gravitational or rotational changes must lead to deformations in the geoid surface and topographic relief. Mörner (1987) concluded that the best-developed models would be those that combine a loading model (e.g. Clarke *et al.* 1978) with a gravitational model. Peltier (1990) also produced a glacial isostatic adjustment and sea-level change model. Calculations were based upon the assumption that meltwater was evenly distributed across the ocean basins. The planetary interior was assumed to be radially stratified with an elastic structure and the rheology linearly viscoelastic. It computed the relative sea-level in a gravitationally self-consistent fashion and predicted that in regions once covered with ice, relative sea-level is falling at a rate of 1 cm per year.

McCabe (1997) argued that the numerical model proposed by Lambeck could not be used for the Irish Sea Basin due to geological constraints that exist. McCabe used palaeo-water depth proxies from biofacies analysis, AMS ^{14}C dating of marine microfaunas and landform evolution within a regional sedimentary basin. The paper disagreed with the origin of the features used, arguing that the delta terraces, marginal banks and mud aprons are marine rather than freshwater features, as previously suggested by Lambeck (1996). This implied that relative sea-level was higher than the modelled data showed. Lambeck also assumed a maximum ice thickness, which McCabe argued was too high. McCabe (1997) concluded that severe limits are imposed on the conclusions and the geodynamics employed by Lambeck (1996). Despite McCabe's research, Lambeck's model was chosen for this study because the sites identified as lacking a sea-level reconstruction were close to sites that Lambeck incorporated into the 1997 model (Lambeck, 1997).

Lambeck (1990, 1997) and Peltier (1990) both based their models upon responses to deglaciation. Lambeck assumed those relative sea-level changes could be observed by studying the crustal response and Peltier assumed that it could be modelled by studying the distribution of meltwater. The advantage of Lambeck's work is that specific predictions have been made for sites in a variety of locations; Australia, NW Europe and Britain, allowing much of the published observational data in these regions to be used to test the model.

It may be seen that several models have been produced to predict sea-level curves around the globe. The creators of the geophysical models have argued that the sea-level curves produced often agree well with observed sea-level curves and that although further work is required the basic assumptions of these models are valid for all regions. However, if these models are to be applied on a local and regional scale, increased observational data is essential to constrain the model.

2.1.7 Tide-gauge records

Tide gauge records can be used to provide valuable information about past sea-levels (Emery & Aubrey, 1991). Records for many sites now date back over 100 years. Thus tide gauge data can provide information on recent sea-level fluctuations, a time-scale most of the techniques described above fail to cover. However, the MSL changes recorded by tide-gauge records include both real changes in the ocean level and those resulting from vertical land movements thus; these need to be separated before tide-gauge data is useful. This problem can be overcome if tide-gauge stations are situated close to one another, as the records can be differenced in order to separate the changes resulting from land movements from the real sea-level changes (Woodworth *et al.*, 1999). Tide-gauge records are also useful as they can provide information about storm surges, which is particularly applicable to monitoring recent sea-level trends. One problem which exists is that not all gauges are set to the same standards and therefore comparison between sites can often be difficult. Thus, current research (Woodworth *et al.* 1999) is trying to create a BI MSL (British Isles Mean Sea Level) which will be comparable to other regions of the world. Examples of sea-level studies which have used tide-gauge records is contained in section 2.2 of this chapter.

2.1.8 Future sea-level and impacts

The future of sea-level rise and potential impacts on the low-lying coastal areas of north west Europe are discussed in Chapter One. However, the work of Jelgersma & Tooley (1992) provides a more detailed review about the problems including, loss of farmland, increase in coastal erosion, increased flooding, increased storm activity to name but a few. Possible future scenarios are also discussed in Chapter One, but the average future rate of sea-level rise is expected to be 0.2m over the next 20 years (IPCC, 2001).

2.1.9 Conclusion

It may be seen from the discussion above that many techniques are available to reconstruct past sea-levels. This chapter has provided a discussion of each of these approaches and included the main advantages and weaknesses of each. The type of approach used must be carefully selected as the results can be biased by the methods involved. The advantages of using a multi-proxy approach have been justified and the limitations of employing modelled data to small-scale studies have been mentioned. The full implications of the approaches employed in this study are discussed in detail in Chapter Nine.

2.2 Evidence for Holocene sea-level change

This section provides an overview of the research that has been undertaken to reconstruct Holocene sea-level changes. The chapter has been broken down into a global perspective, followed by a region by region discussion, focusing on those areas most relevant to this study; North west Europe, then Britain and France, with greater attention paid to the areas of south east England and northern France.

2.2.1 Sea-level change

The pattern of Holocene sea-level change relating to eustatic variations has been widely studied (Daly, 1920; Fairbridge, 1961; Jelgersma, 1966; Morner, 1960; Walcott, 1971; Tooley, 1987; Kidson, 1980, 1982; Van de Plassche, 1980; Shennan, 1986a/b; Carter, 1992). All the above identified the dominant causes of the Holocene period rise in sea-level as being postglacial rebound of the land, eustatic rise in sea-level and the deformation of the Earth due to melting of ice masses. The term eustasy defined any worldwide or simultaneous change in sea-level (Suess, 1885). The term has recently been redefined to include ocean-level changes or any absolute sea-level changes (Lowe & Walker, 1997). However, the use of the term "absolute" is often complicated by the effect of local or regional crustal movements (Lowe and Walker, 1997).

The primary causes of changes in sea-level have been identified as being glacial eustasy, tectono-eustasy, geoidal eustasy and dynamic sea-level changes (Fairbridge, 1961; Lowe & Walker, 1997). Glacial eustasy refers to the changes in volume of the oceans caused by variations in the volume of ice masses resulting from the growth and contraction of ice-sheets. Tectono-eustasy refers to any changes in the level of the oceans resulting from tectonic activity, uplift or subsidence and sea floor spreading, whereas changes in the shape of the earth and the distribution of mass are separately termed as geoidal eustasy. Lastly, the term dynamic sea-level change refers to any short-term fluctuations in sea-level resulting from significant short-term events, for example storms. However, the last of these is considered by many to be temporary and must therefore be excluded from any relative or absolute sea-level studies, which only include long-term changes.

In order for a comparison to be made between sea-level studies, a common sea-level height must be used. Van de Plassche (1986) suggested that this reference water level should be mean sea-level (MSL) because it does not change its spatial configuration relative to the geoid (a mean sea-level surface which extends continuously through the continents) with time because it is directly related to it. MSL therefore provides a constant reference level because it is a function of oceanographic, meteorological and hydrological factors, which include currents, salinity, precipitation, wind stress, river discharge and atmospheric pressure (Van de Plassche, 1986). MSL refers to an average of all tidal levels recorded at hourly intervals. In the UK Ordnance Datum (OD) is used, which is based upon tidal data taken over six years at Newlyn, Cornwall. In France, the equivalent is referred to Nivellement Général de la France (NGF) measured at Marseilles.

Most observational evidence uses Mean High Water Spring Tide (MHWST) as the reference level (Haslett, 1997; Horton, 1999). This is because a regressive peat-clay contact provides an indicative meaning for HAT and a trangressive peat-clay contact indicates deposition at or around MHWST (Haslett, 1997). However, there is a considerable spatial variation between the values of MHWST (Long & Innes, 1993) and it is also now widely accepted that palaeo-tidal levels have changed during the Holocene (Shennan *et al.,* 2000). Therefore, the use of this reference water level is not without its limitations, which must be incorporated into any sea-level study.

2.2.2 Global sea-level change

Previous attempts have been made to show a global pattern of relative sea-level rise (Thorarinsson, 1940; Emery, 1980; Houghton *et al.,* 1995; Shennan *et al.,* 1998). This is now not an accepted practice and has been criticised by many authors (Lambeck, 1990; Pirazzoli, 1991), who stated that the errors incurred when reconstructing sea-level for large areas were too great. In an attempt to establish rates of relative sea-level change on a continental scale Kidson (1980), divided the globe into six independent sea-level zones based upon the distribution of the ice sheets during the time of the last glacial maximum (Kidson, 1980). Fig.2.6 shows these sea-level zones as defined by Clark *et al.* (1978). Within these zones, smaller regions have been intensively studied, and sub-regional sea-level curves produced. An atlas of these sea-level curves is available, providing 77 regional plates of estimated time-altitude graphs of relative sea-level rise for most areas of the world based upon previously published research (Bloom, 1977; Pirazzoli, 1991).

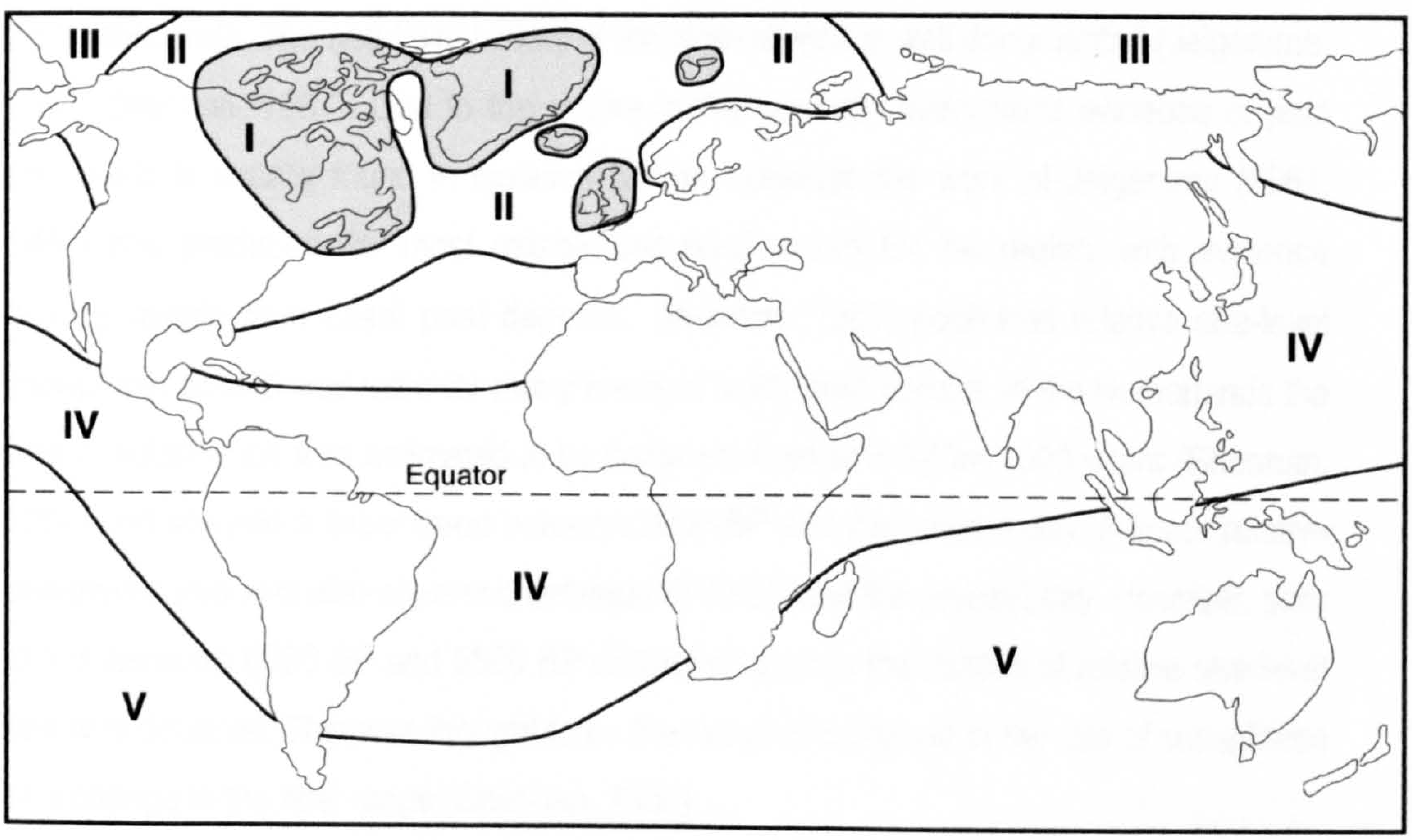

Fig. 2.6 Global sea-level change zones. After Clark *et al.* 1978

2.2.3 North west Europe

Since this research is focusing on south east England and northern France, it seems appropriate to describe the pattern of sea-level change for north west Europe as a whole, before the study sites are discussed in detail. The Scandinavian coastlines of north west Europe offer a complicated historical sea-level pattern, since they are closer to the former glacier margins. Mörner (1969) used sedimentological and archaeological evidence to produce a relative sea-level curve for the Baltic Sea, which showed three rapid regressive sea-level movements for Stockholm, Sweden (2650–2550 BP, 1600–1500 BP, 980–900 BP). Peat bog records were used to correlate Late Holocene changes in climate with the relative sea-level movements, concluding that dry periods coincided with sea-level changes.

An examination of the sea-level data for Norway (Shennan, 1987) however revealed a curvilinear relationship between relative sea-level and subsidence, rather than a linear relationship as seen in most other north west European sites. In addition to this, Norway also does not exhibit any shoreline oscillations (Shennan, 1987).

Most low-lying coastlines in north west Europe are now under threat from rising sea-level (Tooley & Jelgersma, 1992). Of particular importance are the coastlines of Belgium and the Netherlands. The sea-level history of the Netherlands is well documented (Jelgersma, 1961; Shennan, 1987). Due to the nature of the coastal environment evidence of past sea-levels is usually found in isolation basins, however the work of Jelgersma (1961, 1980) has produced the most reliable sea-level record for the region, with evidence coming mainly from basal peat deposits. Shennan (1987) published relative sea-level curves and subsidence rates for many areas of north west Europe. In the Netherlands the rate of subsidence was estimated to be between -0.44 and 0.49m/1000 years (Shennan, 1987) and showed a linear trend between 7000 BP and the present day. A linear relative sea-level curve was also observed between 5500 BP and the present day. However, prior to this between 6500 BP and 5500 BP distinct change in the pattern of relative sea-level rise was detected. This was thought to be the result of a change in the rate of subsidence or a change in the tidal range (Shennan, 1987).

It is estimated that over half the Netherlands currently lies below mean sea-level, making it particularly vulnerable to flooding by rivers and storm surges. Postglacial rise in sea-level and tectonic subsidence make the low-lying coastal plains especially susceptible to flooding (Jelgersma, 1992). The pattern of Holocene sea-level change in the Netherlands can be broken down into three main phases. The early-Holocene, from *c.* 9000 yrs BP, was characterised by a rapid rate of sea-level rise, similar to that recorded across much of north west Europe. Molan (1997) estimated this rate of sea-level rise to be 80cm per century. Throughout the mid-Holocene, from *c.* 5500 BP, however a marked decline in the rate of sea-level rise may be observed and the pattern of coastline retreat was reversed. The rate of sea-level rise had fallen sufficiently to allow sedimentation to exceed sea-level rise. Thus, until 2000 yrs BP, the coastline of the Netherlands can be seen to progress. However, by the time of the late Holocene, a return to a rising sea-level could be seen, which caused further coastline retreat.

The coastline of the Netherlands has retreated 200m and past sea-level rise has been estimated at 15-20cm over the last 100 years (van Malde, 1992). With a predicted rise in sea-level for the next 100 years of 1m, much greater than the IPCC (2001) predictions, (Jelgersma, 1992) this would place most of the coastline and plain below sea-level.

The Holocene history of sea-level change in Belgium, however appears to show a marked difference, largely attributed to the differential crustal movement which is experienced (Denys & Baeteman, 2001). The early-Holocene pattern depicts a rapidly rising rate of relative sea-level, until *c.* 7500-7000 cal yrs BP, when a marked decrease in the rate was recorded. A second period of slowing down was also seen *c.* 5500-5000 cal yrs BP (Denys & Baeteman, 1995). A Mid Holocene rise in sea-level was recorded *c.* 4000-3000 cal BP (Baeteman, 2001)

The Belgian coastal plain currently lies at approximately mean sea-level (Baeteman *et al.* 1992) and is protected by a series of dykes and dunes. Tide gauge records for the last century show a linear increase of 0.01m per decade for mean sea-level. This coastline is at most risk due to the nature of its sediments. The unconsolidated peats and clays that dominate the Holocene geology, make it extremely vulnerable to erosion and thus flooding.

Research on the coastal estuaries in western Germany revealed a number of clastic deposits and intercalated peat deposits, suggesting that there had been a number of changes in storminess (Shennan, 1987). A linear subsidence trend was noted between 6000 BP and the present day. However, prior to this it is believed the rate of subsidence had been greater. A linear trend of relative sea-level was also presented between 5000 BP and the present day. An important potential error in interpretation was also presented, stating that the fluctuations that had been previously recorded (Linke, 1982) were actually the result of different interpretations exaggerating the variability (Shennan, 1987).

Holocene sea-level changes in the North Sea region are well documented, and the above section has simply provided a very brief summary of the main findings. Shennan (1987) provided an excellent discussion on both the pattern of relative sea-level change and the rates of crustal uplift/subsidence as determined from the eustatic sea-level curves. In addition the work also provided a useful discussion of the errors involved in employing different methodologies. A maximum fall in sea-level is thought to have reached -110m (Jansen *et al.*, 1979).The sea-level record for the North Sea area reveals a high relative sea-level during the early Holocene, with the North Sea and the English Channel being connected at around 8000 yrs. BP (Shennan, *et al.*, 2000). The period between 8000 and 6000 yrs BP, experienced a slight reduction on the water depth, suggesting relative sea-level had fallen. By around 5000 yrs. BP the relative sea-level in this area can be seen to start to rise again, reaching a maximum around 4000 yrs BP (Shennan *et al.*, 2000). It can be seen that this a quite a different pattern to that displayed in the more northern regions of north west Europe, in particular those that are closer to the margins of the ice sheets.

The sea-level studies carried out in north west Europe have clearly highlighted the importance of ice sheet distribution in influencing patterns and rates of relative sea-level change since the time of the last glacial maximum. Thus, making it difficult to describe a pattern of relative sea-level change for this large area.

Tide-gauge records

Research on the short-term past changes in sea-level using tide-gauge records has shown that the impact of short-term, high rates of tectonic activity upon the Dutch coast complicates matters. Kooi *et al.* (1998) documented high rates of short-term tectonic movements experienced in the Netherlands over the last century. Tide-gauge records record tectonic activity as well as relative sea-level movements. If the sea-level signal is to be obtained the isostatic factor needs to be removed from the results. Kooi *et al.* (1998) concluded that correcting of tide-gauge records to account for the glacio-isostatic effect could not provide an accurate measure of eustatic sea-level rise because of the uncertainties surrounding current estimates.

2.2.4 British Isles

Britain as a whole has experienced a rise in mean sea-level throughout the Holocene, with a higher rate of relative sea-level rise recorded over the last 4,000 years (Kidson and Heyworth, 1973; Greensmith and Tucker, 1973; Tooley, 1974 and Jardine, 1975; Orford et al. 2000). In order to determine the sea-level history for the British Isles it is necessary to divide the country because the patterns of sea-level change vary significantly between the regions. The types of environments that are available to study also vary between regions; raised beaches (Sissons, 1976) and isolation basins (Shennan et al. 1994) tend to be found in emergent coastal areas such as Scotland, whereas back-barrier environments (Long and Innes, 1993) dominate the submerging eastern and southern coasts.

In an attempt to classify the general pattern of Holocene sea-level change in Britain, three classifications have been presented (Tooley, 1978). First, a rapidly rising sea-level until 3,000 years ago which rose to 3m above present-day level (Fairbridge, 1961). Secondly, a steadily rising sea-level throughout the Holocene (10,000 years) reaching but not exceeding present-day sea-level *c.*3,600 BP (Godwin *et al.* 1958). Thirdly, a continuously rising sea-level throughout the Holocene, diminishing with time but persisting until the present day (Shepard, 1960, 1963). It will become apparent throughout this chapter that it is not possible to assign a pattern of sea-level change on such a large scale. In order to identify the main patterns of sea-level change, studies need to be undertaken at a smaller scale.

Included in all sea-level studies in Britain is the ongoing debate surrounding sea-level studies in England relates to the influence of crustal uplift. When attempting to determine causes of relative sea-level change it becomes necessary to take into account both the movement of the sea relative to the land and the movement of the land relative to the sea.

Shennan (1989b) produced scatter plots of subsidence and uplift for fifteen areas of Britain, noting "the exponential decay of uplift to the north, and recent linear subsidence to the south" (Shennan, 1989b: p.86). The estimated rates for Britain are shown in Fig. 2.7. It can be seen that southern regions are experiencing land subsidence while the northern regions are experienced relative uplift.

Shennan (1989b) describes this as coastal down-warping throughout the south during the past 4,000 years, with rates of up to 2 mm per year in Norfolk being cited. Long & Shennan (1993) used the model proposed by Shennan (1989b) to examine crustal subsidence in the East Kent Fens and Thames estuary in southern England and sites in Northumberland, the Tees estuary and Hartlepool in northern England. The results confirmed and quantified the pattern of subsidence in the south and uplift in the north. This pattern creates difficulties in distinguishing between changes in absolute sea-level and the effects of crustal subsidence, for example the work in the Thames estuary, which will be discussed later in detail (Devoy, 1979; Haggart, 1995).

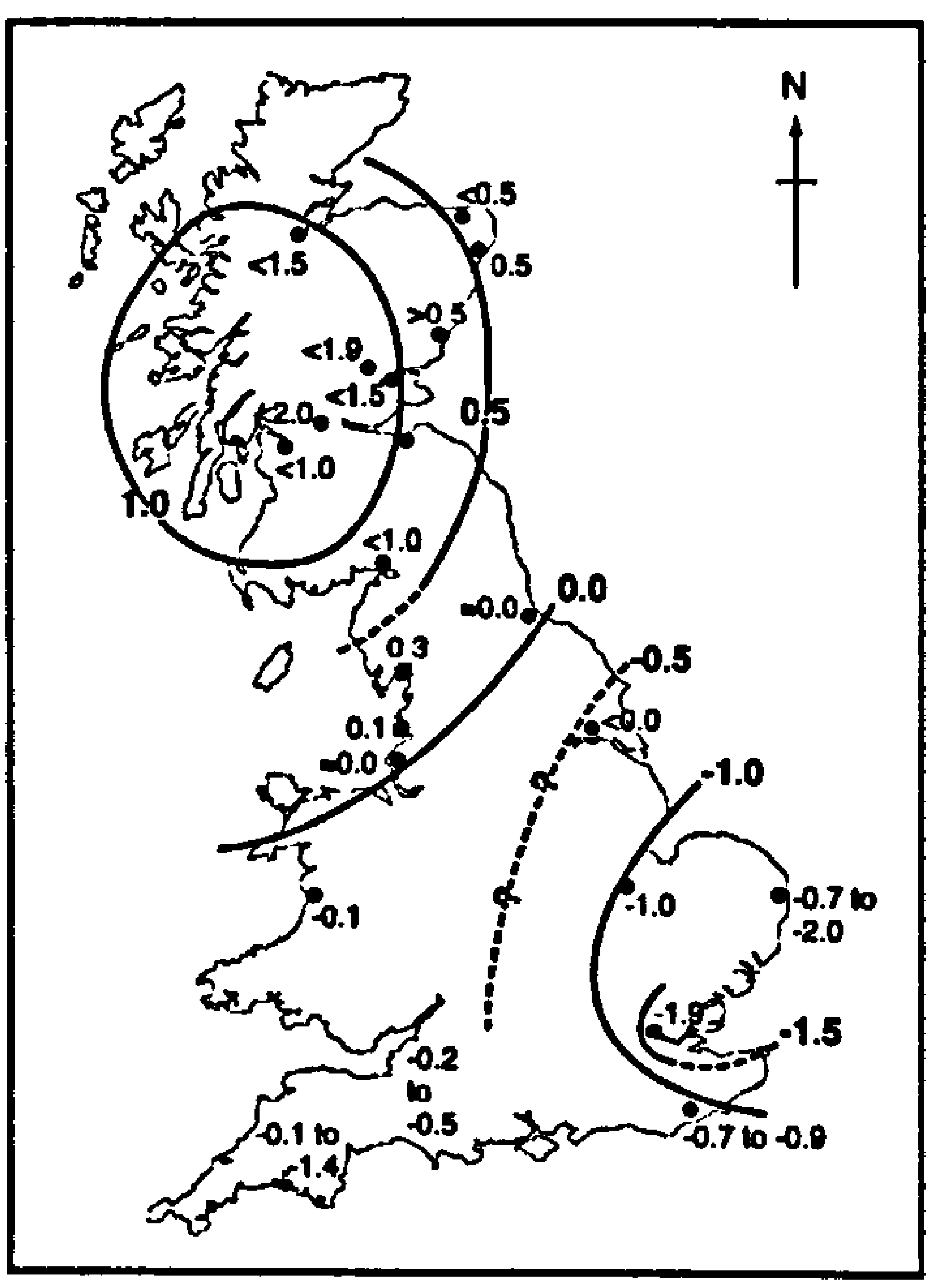

Fig. 2.7 Estimated rates of crustal movement in Britain (mm/yr) (Shennan, 1989)

Ireland

The Holocene sea-level record for Ireland exhibits a rising rate of relative sea-level, with Late-Holocene estimates placed at between 0.6mm and 1.1mm per year (Carter *et al.* 1989). Research has revealed differences in the sea-level signals between the north and south of Ireland. In the north, sea–level is still falling, and an east to west trend in the timing of relative sea-level movements can be seen, which is believed to be isostatically-controlled (Carter *et al.* 1989). The coastal sediments on the north west coast are dominated by intertidal peat deposits, which Shaw & Carter (1994) believed were deposited following geomorphological changes, which caused the estuaries to become isolated from marine influence, allowing peat to form in the shadow of a barrier. The freshwater peat deposits described above capped marine sediments overlain by silty peat, indicating the presence of a saltmarsh environment. The impact of coastal features, such as barriers (Orford, 1988) can be seen to complicate the sea-level record, similar to examples from the south coast of England discussed later. The south of Ireland however seems to show a continuously rising sea-level, the rate of which has decreased in the past 5,000 years (Carter *et al.* 1989). Similar patterns and rates to the British mainland can be observed, but with one main difference. The east to west gradation in the timing and magnitude of the Holocene peak that is recorded in the north of Ireland is not reflected in Britain and therefore must be the result of local isostatic controls.

Wales

Published sea-level research in Wales is scarce. Several curves have been published but many of these were based on relatively small amounts of data, with few radiocarbon dated index points being used. In North Wales, Heyworth & Kidson (1982) produced a curve showing a gently rising pattern of sea-level over a relatively short period of time (8,500 – 4,500 years BP). Fig. 2.8 provides the sea-level curves produced for north Wales; Cardigan Bay, west Wales and the Bristol Channel, south Wales. However, the curve was only based on two radiocarbon dates and therefore must be accepted with some caution. Further work has been carried out in Cardigan Bay, north west Wales revealing a smoothly rising sea-level curve (see Fig. 2.8). Initially the rise in sea-level was fairly rapid, followed by a more gently rising curve after 6,000 years BP, a pattern more similar to the southern parts of the UK (Long & Innes, 1993; Scaife & Long, 1995).

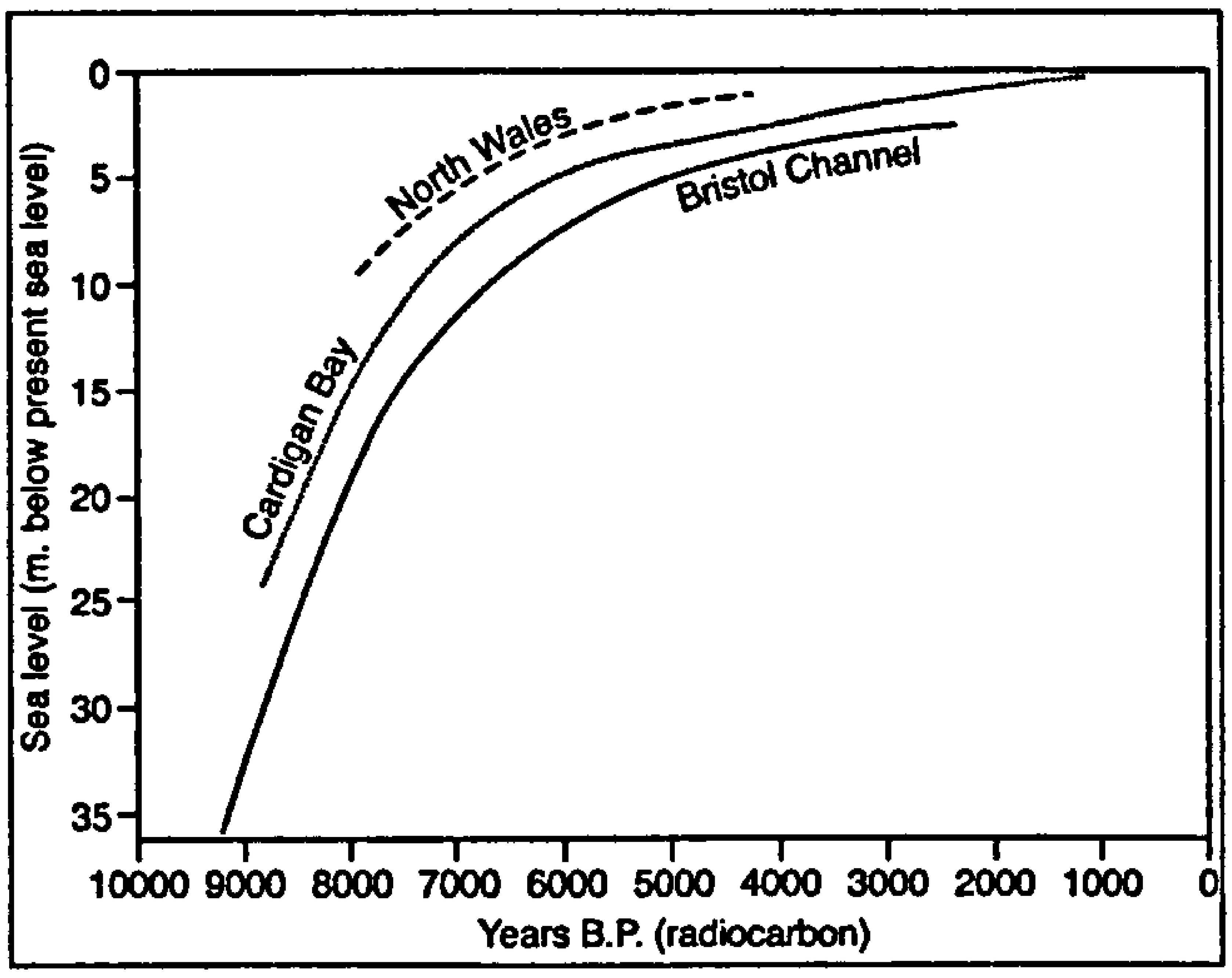

Fig. 2.8 Sea-level curves for a) North Wales b) Cardigan Bay c) Bristol Channel

After: Heyworth & Kidson (1982)

The sparse nature of research in Wales makes drawing a conclusion about the pattern of relative sea-level change difficult. However, tentatively it can be seen that sites in the north of Wales show a pattern of Holocene sea-level rise more akin to that found in southern Scotland and northern England and south Wales shows a greater similarity to southern England, most likely the result of proximity to the margins of the ice sheets.

Scotland

The collection of Holocene sea-level data from Scotland requires a different approach to that taken for most of the sites previously discussed. The sites studied in Scotland are all examples of emergent coastlines and therefore evidence tends to be derived from isolation basins and raised coastal features such as marshes, spits and beaches. Many of these emergent coastlines present a Holocene sea-level history quite different to that previously discussed, with some many showing evidence of a higher than present-day sea-level (Sissons, 1981a/b; Firth *et al.* 1995; Shennan *et al.* 1995; 2000).

Evidence of Holocene sea-level change in Scotland appears to have been controlled by isostatic forces, however the timing and pattern of Holocene sea-level change coupled with isostatic rebound varying greatly between sites. Some sites have revealed evidence of crustal uplift, while others simply show a fall in relative sea-level. Variations in the rate and amount of uplift experienced also vary, with a clear difference being observed between sites in east and west Scotland. For instance, the relative uplift that has taken place since the last glacial maximum has lead to a huge variation in the pattern and timing of sea-level change across the Beauly Firth (Haggart, 1986, 1989). Two periods of falling relative sea-level were identified; between 9600 yrs BP to 8800 yrs BP and post-6400 yrs BP, and a period of relative sea-level rise between 8800 and 7200 yrs BP (Haggart, 1986). The variations observed between sites at Beauly Firth were attributed a differential crustal movement between the north and south shores of *c.* 2m, (Lloyd *et al.*, 1999). In north west Scotland (Shennan *et al.*, 2000) it can be seen that the Devensian and early-Holocene periods were characterised by a marine regression, with sea-level falling from 36.5m OD 15900 cal yr BP to the early-Holocene minimum. There is little evidence to suggest that sea-level fell below the present-day level in this region, with the mid-Holocene sea-level maximum (8000-5000 cal yr BP), estimated to have been 6.5m above present-day.

Eastern Scotland also witnessed a post-glacial fall in relative sea-level, followed by a mid-Holocene rise in sea-level (Firth *et al.*1995; Shennan *et al.* 2000a,b). However, the early- to mid Holocene appears to have been characterised by three episodes of increasing then decreasing sea-level rise; 10000-9000 ^{14}C years BP; 9000-8400 ^{14}C years BP and 8400-5500 ^{14}C years BP, with sea-level being around 1-3m below mean tidal levels (Smith *et al.* 1999), highlighting the first major difference between east and west Scotland. The marine transgression ended between 6650 and 6800 years BP, marked by the Main Postglacial Shoreline (Sissons, 1981a). The mid- to late-Holocene period was then characterised by a period of falling sea-level. Throughout the mid-Holocene spits were able to develop on regressive coastlines (Firth *et al.* 1995) suggesting a low or falling sea-level at this time and studies of the late-Holocene (Shennan *et al.* 1995) indicate that sea-level continued to fall. These studies of the Scottish coastline display characteristics more comparable to near-field sites and suggest that isostatic factors have played the dominant role in determining the Holocene pattern of sea-level change.

Northern England

Many areas of northern England have been extensively studied to identify the major patterns of relative sea-level rise and research has revealed that patterns show a closer similarity to the Scandinavian countries of north west Europe than the rest of England

(Shennan, 1987). Research shows that a relative fall in relative sea-level has occurred over the last 10,000 years.

Tooley (1978) carried out an extensive study into the pattern of relative sea-level change in north west England during the Flandrian. The work identified 18 phases of sea-level change for the Flandrian, beginning with a rapid rise until 7600 yrs. BP, when the rate of sea-level rise began to decline. A period of falling sea-level was then recorded until 6800 yrs BP. A series of rising and falling periods followed until sea-level reached its maximum, 4500 yrs BP (Tooley, 1978). The late-Holocene was dominated by a rising and falling relative sea-level, with the highest altitude being recorded 830-805 yrs BP.

Shennan *et al.* (1995) also identified several sites in the north west of England, which revealed a relative fall in sea-level and highlighted the differences between the north and south regions of England, revealing the important role that crustal subsidence plays. Zong and Tooley (1996) carried out a detailed study of Morecambe Bay using both diatom and pollen as indicators of sea-level change and incorporating the effects of crustal movements. This study revealed a rapid rate of sea-level rise, which fluctuated between -8 mm per year and +12 mm per year. Zong & Tooley (1996) concluded that isostatic uplift had influenced the coastline but had been interrupted by a period of rapidly rising sea-level. Subsequent uplift had occurred but at a decreased rate. The phases of subsidence identified at this site should be accepted cautiously, as the paper itself concludes. As in all sea-level studies in north east England, the rates of subsidence should have been corrected for compaction and consolidation of the sediments and changes in the tidal regime.

Plater *et al.* (2000) as part of a study to determine sediment flux in the Tees Estuary, produced a sea-level curve using sea-level index points taken from intercalated peats (Shennan, 1986), showed a slowing down in the rate of relative sea-level rise during the mid-Holocene. Plater *et al.* (2000) revealed that relative sea-level change was a major control on sediment flux, in particular decelerating rates of sea-level rise. The study also made some useful suggestions about the late-Holocene increase in tidal level, thought to result from increased marine influence. The increase in marine activity was attributed in part to climate- and human-induced changes in the sediment supply of terrestrial material (Plater *et al.*, 2000).

Shennan *et al.* (2000) produced a summary of relative sea-level change for eastern England based upon research in Northumberland, the Tees Estuary, the Humber, Lincolnshire marshes, Fenland and North Norfolk (see Fig. 2.9). The spatial and temporal differences observed were attributed to regional factors, including isostatic glacial rebound and water load contributions.

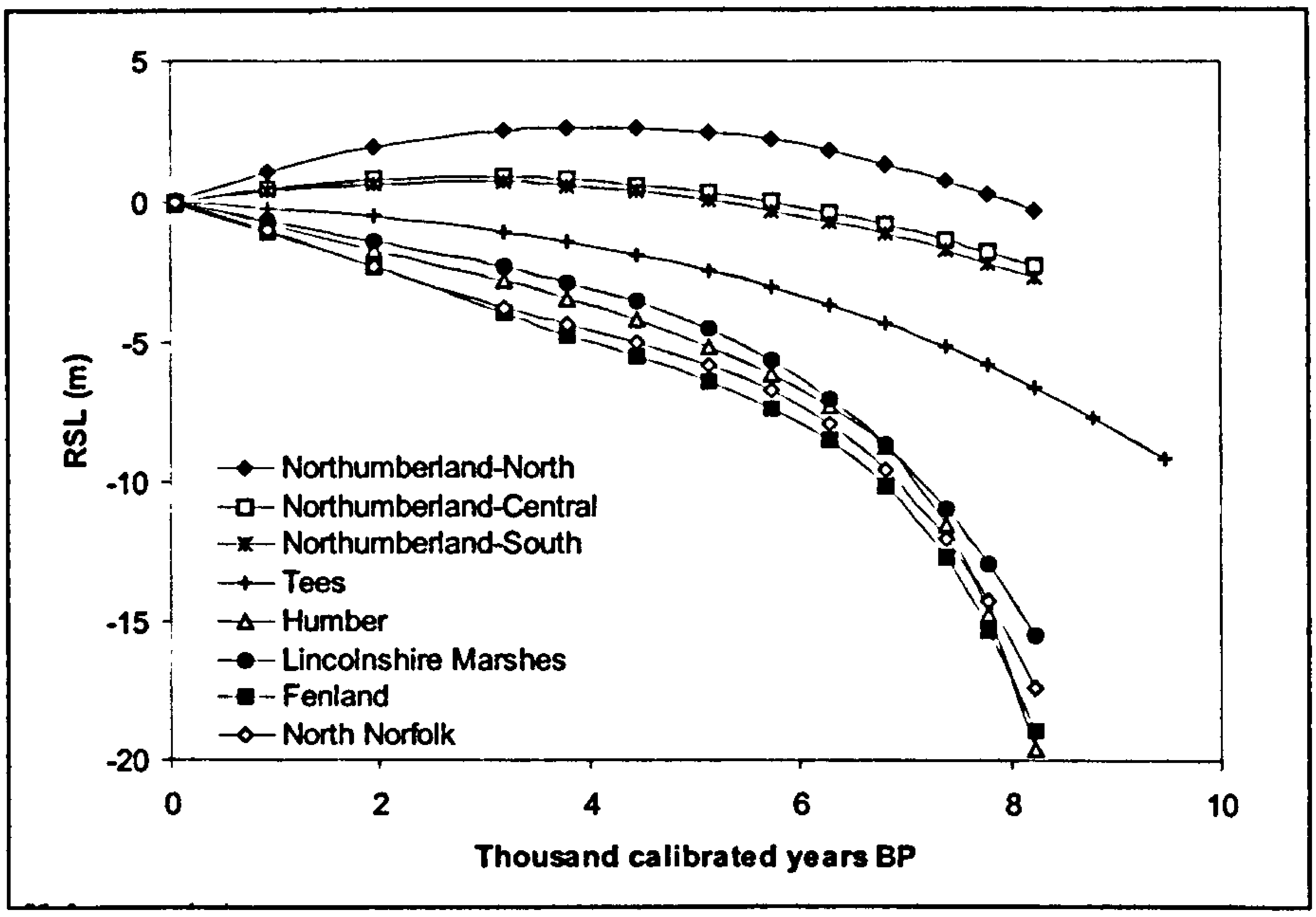

Fig. 2.9 A relative sea-level curve for the eastern England After: Shennan *et al.*(2000).

It can be seen from the studies discussed above that the pattern of relative sea-level change in north west Europe as a whole and northern England is complicated by the influence of crustal movements. In many areas it is evident that sea-level is falling. The incorporation of a crustal effect is thus a crucial component when trying to elucidate relative sea-level changes and the work of Shennan (1989) must be considered when reconstructing sea-level change in Britain.

Tide-gauge records

Woodworth *et al.*, (1999) have shown that average mean sea-level in the North Sea has risen by 1mm per year more during the past century than Holocene sea-level records would have suggested. This would indicate a rapid rising late-Holocene sea-level.

Norfolk and The Fens

The Holocene sea-level history of Norfolk and the Fens is well documented, largely due to the work carried out by the Fenland Project (Waller, 1994). In an attempt to determine the depositional history of the region, Shennan (1992) produced models of coastal sequences from the intercalated inorganic and organic deposits, proposing three hypotheses. The first discussed evidence for a stable barrier present across The Wash suggested by Swinnerton (1931) and Robinson (1968, 1981), which accounted for the presence of peats and clays. The second hypothesis proposed a migrating barrier or series of barrier islands. The barriers will have acted as a protection from the sea, but would have experienced regular breaching allowing brackish and marine sediments to be deposited. Thirdly, Shennan (1994) proposed an open coast. A marine transgression would have resulted in the re-working of Flandrian sediments producing a low-energy intertidal zone. The third hypothesis included the presence of barriers but concluded they were not significant in controlling the depositional environment. The controlling factors in the pattern of coastal evolution were divided into five new hypotheses. The first proposed the rate of sea-level change examining the relationship between regional eustasy and the series of sea-level index points. The second hypothesis examined the morphological features as controls i.e. the presence or absence of barrier features. Hypothesis three examined the sediment supply from the littoral zone, hypothesis four studied the influence of tidal and wave climate and finally hypothesis five examined the terrestrial and fluvial input of sediment and water. The palaeogeography of the Fens was reconstructed using a series of maps and a substantial number of radiocarbon-dated events were provided for each phase of evolution.

Waller (1994) provides a complete history of sea-level change in the Fens by examining eight sites. Most notable is the onset of peat formation across most the region at around 6500 yrs BP. This suggests a relative fall in sea-level must have taken place to allow such extensive peat growth. This is followed by a clear increase in marine activity around 3000-3500 yrs BP, at nearly all the sites examined. Shennan (1994) concluded that the Flandrian period had been dominated by positive sea-level tendencies, with a few short-lived ill-defined negative tendencies recorded at *c.* 5800 BP, 4500 – 4150 BP, 3400 – 3150 BP, 3000 – 2700 BP and 1800 – 1650 BP. The first hypothesis, rate of sea-level rise, was accepted as the most likely controlling factor for coastal evolution in the Fens. The average rate of sea-level rise prior to *c.* 4000 BP was estimated at 2.5-3mm/yr and *c.*

1mm/yr after 4000 BP, based on subsidence rates. Shennan (1994) concluded by stating that rate of sea-level rise, the associated changes in the palaeogeography and the sedimentary environment together could explain the pattern of coastal evolution observed in the Fens. These findings contradicted the earlier work of Funnell and Pearson (1989) who examined the coastline of North Norfolk examining the pattern of Holocene sedimentation. Their work concluded that the Late Glacial topography strongly influenced the pattern and that although relative sea-level movements can be identified they were not the controlling factor in the pattern of coastal evolution. It is likely that Funnell and Pearson (1989) detected local factors in the sea-level signal. The extensive work across the entire region carried out as part of the Fenland Project (Waller, 1994) enabled both local and regional signals to be detected, thus building a much clearer picture of coastal evolution.

Southwest England

The rising pattern of Holocene sea-level change in southwest England has been established through the collection of a number of published radiocarbon dates in the Bristol Channel and Somerset Levels (Heyworh & Kidson, 1982; Haslett *et al.* 1998). The sea-level curves produced for the last 10,000 years for the regions show a close correlation and do not suggest sea-level has ever been higher than the present (Fig. 2.10). In the Bristol Channel a gently rising sea-level curve was produced (Heyworth & Kidson, 1982) similar to that produced for Cardigan Bay, Wales, which contradicted earlier work by Devoy (1979) who had shown seven marine transgressions. The Bristol Channel signal is complicated by the large tidal range that the estuary experiences and the problem of compaction and consolidation of sediments (Allen, 1991). Heyworth & Kidson (1982) also discussed the errors involved in sea-level studies, highlighting the importance of using a common datum and allowing for the errors incurred whilst levelling, as well as taking into account changes in tidal regime.

Scaife & Long (1995) compared the sea-level history of Caldicot Pill, in the Severn Estuary, to that published for the Bristol Channel (Heyworth & Kidson, 1982) and provided a detailed pattern of sea-level rise, which showed a rapid rise until 6000 years BP followed by a falling rate of sea-level rise. Marine conditions are thought to have been absent between *c.*6500 and 5000 years BP, shown by the transition from marsh deposits to reed swamp and then carr woodland, with freshwater rivers and lagoons present.

Scaife & Long (1995) argued against the smooth curve proposed by Heyworth & Kidson (1982) and concluded that any oscillations recorded in the sea-level signal could not be attributed to a variation in sea-level and were a function of varying sedimentation rates, tidal variations and the action of coastal barriers.

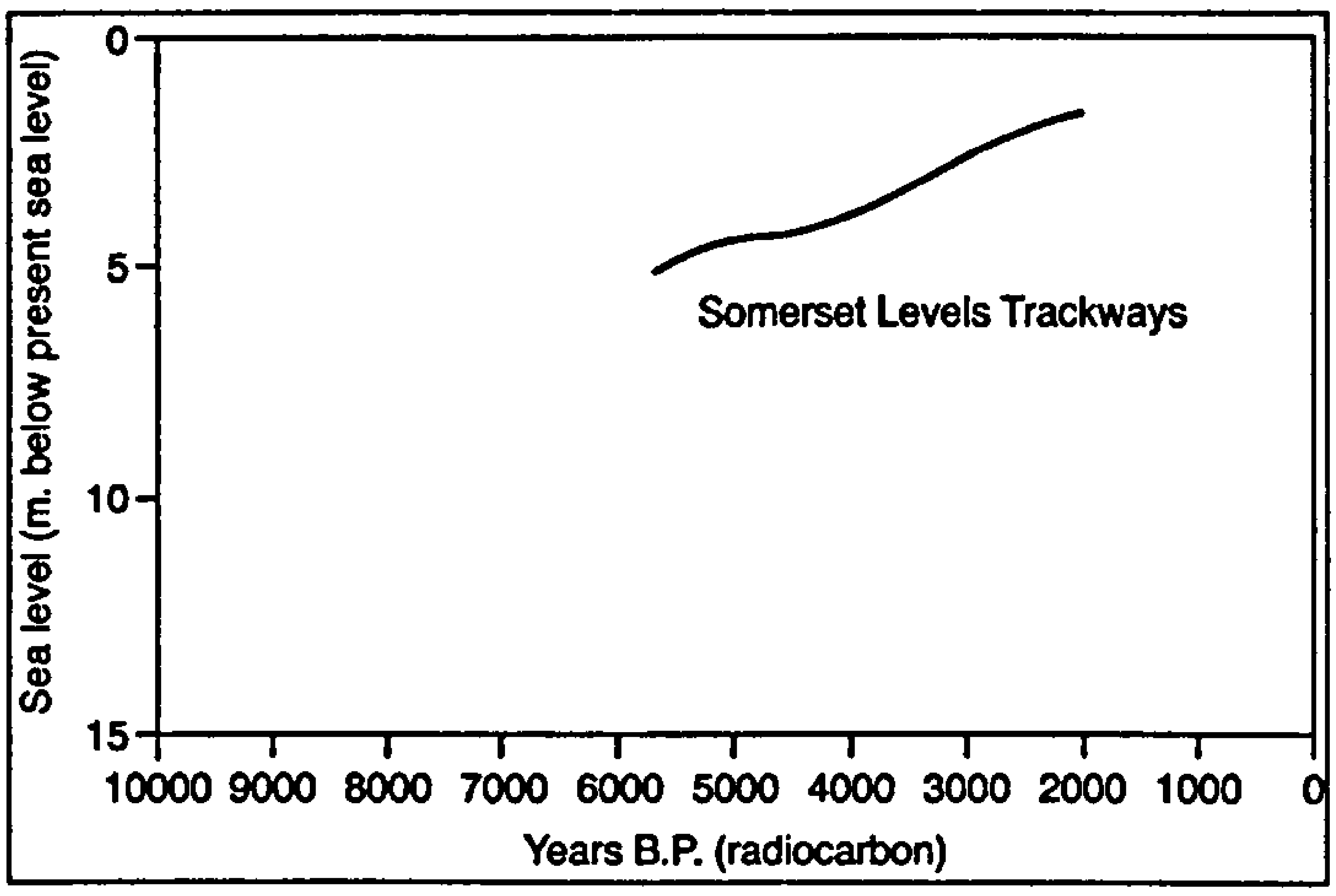

Fig. 2.10 Sea-level curve for the Somerset Levels, south west England

After: Heyworth & Kidson (1982)

The intercalated peat deposits recorded across the Severn Estuary are thought to be the result of a slowing but unsteady rising sea-level (Allen, 2000; Haslett *et al.* 2000). Sediment compaction caused the thickness of these deposits to vary in an eastward direction across the estuary with thicker deposits recorded furthest from the sea (Allen, 2000). A reconstruction of the pattern of Holocene sea-level change at Nyland Hill, Somerset Levels, using foraminifera and molluscs revealed a rapidly rising sea-level throughout the Early Holocene, suggesting an environment dominated by saltmarsh and mudflats. This was followed by a slower rate of rising sea-level during the mid-Holocene, with foraminifera indicating a mid to high saltmarsh environment, as well as the possibility of a fall in sea-level illustrated by peat-forming mire environments. The late Holocene sediments indicated that reclamation of the land exceeded the rate of sea-level rise (Haslett *et al.* 2000).

Additional work in southwest England by Haslett *et al.* (1998) resulted in the construction a sea-level curve for the Somerset Levels using pollen, diatoms and foraminiferal data.

New radiocarbon dates suggested that there had been a very rapid 'instantaneous' rise in relative sea-level, however Haslett *et al.* (1998) suggested the evidence for this rapid rise may have been the result of localised sediment compaction and did not truly reflect a relative sea-level rise. This inconsistency may have been resolved if more than four sea-level index points had been obtained, allowing the work of Heyworth & Kidson (1982) to be adequately compared with the work of Haslett *et al.* (1998).

In west Cornwall, the pattern of relative sea-level change was established at Marazion Marsh (Healy, 1995) and compared to the curves of Heyworth & Kidson (1982). Healy (1995) showed an oscillating sea-level curve, compared with the smooth curve produced by Heyworth & Kidson (1982). Healy (1995) criticised the work of Heyworth & Kidson (1982), stating that sedimentation would have produced coastal features that would have affected the position of relative sea-level.

The above discussion shows that southwest England experienced a rapid rise in relative sea-level throughout the early-Holocene. This was followed by a decline in the rate of relative sea-level rise from the mid-Holocene onwards.

Southern England

The southern coastline of England has been extensively studied and sea-level index points have been used to establish relative sea-level curves for many estuaries along the coast. It is clear that the record found on a subsiding coastline is unlike that found on an emerging coastline, such as those found in Scotland.

There appears to be a marked difference between central southern England and south east England, in the altitude and pattern of Holocene sea-level change. Although a similar trend can be recorded, showing a gradually rising sea-level since around 6000 cal. yrs BP, Long & Tooley (1995) found sea-level index points in Hampshire plotted 2-3m above similar aged index points from sites in south east England, revealing a west to east gradient in the altitude of sea-level index points along the south coast of England. After 5000 cal. yrs BP, a similar pattern was recorded between Romney, Sussex and Hampshire but not Thames or East Kent Fens. This difference was attributed to differential crustal movements thought to have taken place between 5000-4000 cal. and 2000-0 cal. BP, and the presence of the Variscan Front. The study highlighted important differences between sites in south east England and northern France, but did not provide any cross-channel sea-level data to support the theory, simply discussing the crustal effects. Further work has identified a sea-level still-stand, thought to have taken place around 3600 yrs BP (West, 2000) in the Solent, which was responsible for the peat layer which formed along the southern coast of England.

Long *et al.* (2000) described an early Holocene expansion in Southampton Water, resulting from a rising sea-level. As with most sites in southern Britain, the mid-Holocene was characterised by phase of peat accumulation, however the authors argued that a simple transgressive model of estuary development does not satisfactorily explain the extensive peat formation and tripartite sequence observed at the site. Long *et al.* (2000) concluded that the rate of relative sea-level rise must have declined significantly for this sedimentary sequence to have developed. At Southampton Water the late-Holocene was marked by a return to minerogenic sedimentation and subsequent in-filling of the estuary. Regional processes were thought to be operational throughout the Holocene, resulting in a similar pattern of estuary development observed at other sites along the south coast.

The late-Holocene pattern of sea-level change has been determined using both ^{14}C chronology and ^{210}Pb with sediment accretion rates (Cundy & Croudace, 1996 and Long *et al.*1999). The late-Holocene period has seen a rise in relative sea-level of 1.99m at Poole Harbour (Long *et al.* 1999). This appears to have been coupled with a rise in sediment accretion rates, which rose from 0.29mm a^{-1} to 1.14 mm a^{-1}, which the authors suggest point towards an acceleration in relative sea-level rise. Cundy & Croudace (1996) demonstrated that there has been a rise in the average rate of mean sea-level rise since the mid-Holocene. 6500 years BP the average rates was 1.2mm yr^{-1} compared with recent sea-level rise (AD1900) of 4-5mm yr^{-1}.

In a comprehensive palaeoecological study, Edwards (2001) used a foraminiferal-based transfer function to study Poole Harbour, Dorset, concluding that four phases of sea-level change had occurred over the past 5000 years. Table 2.4 summarises these relative sea-level movements.

Relative sea-level movement	Date
Increase in the rate of relative sea-level rise	*c.* 400 – 200 cal. yr BP - present
Rising relative sea-level	*c.* 4700 cal. yr BP – *c.* 2400 cal. yr BP
Rising sea-level, followed by a period of stability	*c.* 1200 cal yr BP – *c.* 900 cal. yr BP
Stable to falling relative sea-level	*c.* 2400 cal yr BP – *c.* 1200 cal. yr BP

Table 2.4 Relative sea-level movements, Poole harbour, southern England
After Edwards (2001)

Southern England has clearly witnessed a variation in the altitude and rate of Holocene relative sea-level, suggesting that differential crustal subsidence could have played a significant role in the pattern of sediment deposition. Although the pattern and timings appears to be similar to the findings at other sites in south east England, sea-level index points plot above those from other sites. This west-east trend highlights the importance of carrying out comparative research, using like methodologies.

Tide-gauge records for southern England

Research by Woodworth *et al.,* (1999) has provided evidence to show century-scale accelerations in mean sea-level if between 0.4-0.8mm per year. This was done using a combined ocean tide and storm surge numerical model. At Portsmouth for example a flattening off in the time series can be seen over the past 50 years. Rates were 5mm per year compared with 1.45mm per year at the present. The results suggest that the rising rates of relative sea-level seen throughout the late-Holocene may be stabilising.

2.2.5 South east England

This section has been divided the south east of England into four regions: Essex, the Thames Estuary, Kent and Sussex. This is to highlight the importance that scale and local processes can have upon the sea-level record. A map showing the location of these sites may be found in Fig. 2.11.

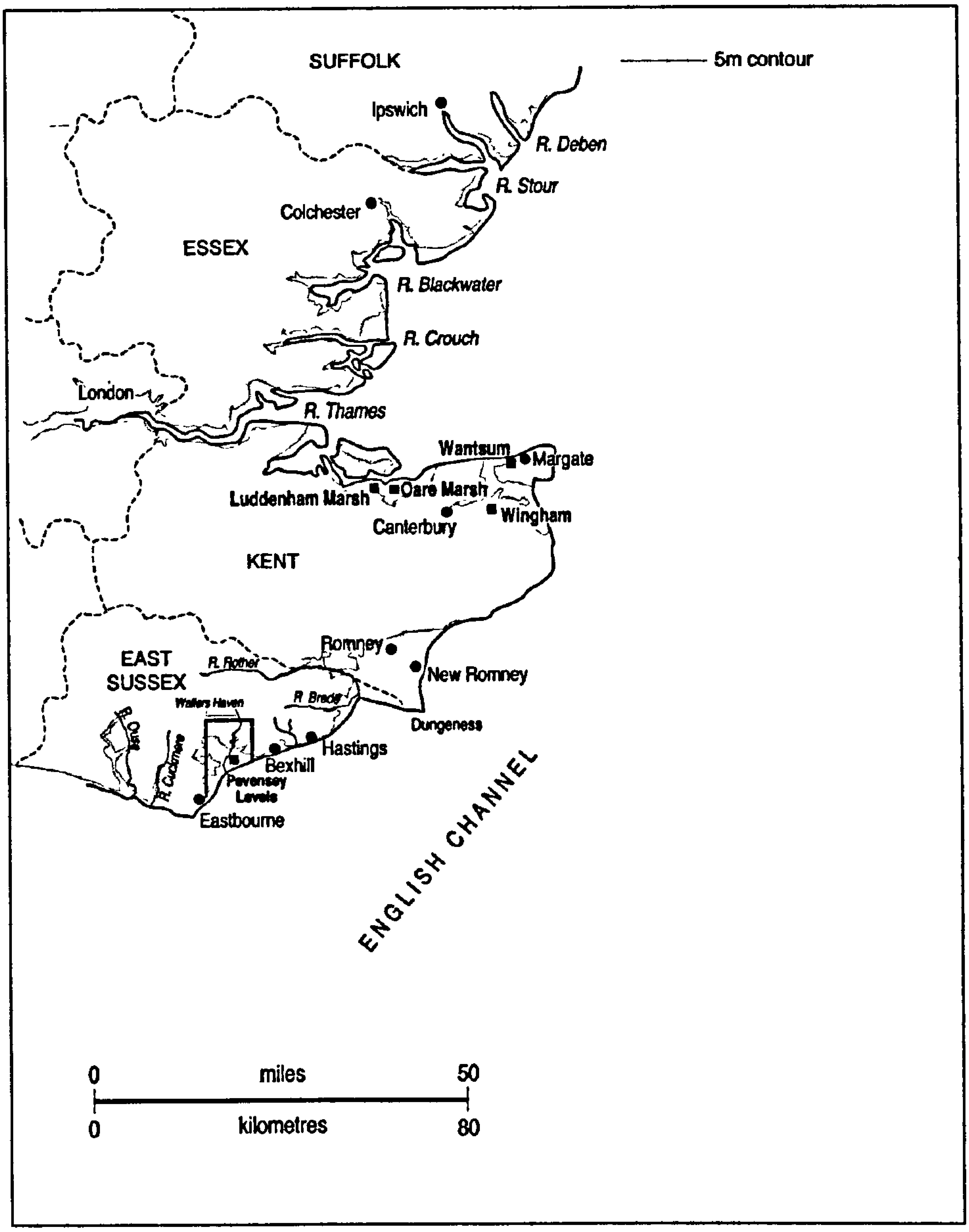

Fig. 2.11 Map of sites in south east England
(Boxes denote the study sites)

Essex

The sea-level record for the Essex coastline remains incomplete, with only a small number of studies having presented just 10 sea-level index points to date (Horton *pers. comm.*). Greensmith and Tucker (1971, 1973, 1980) studied the Essex coastline in an attempt to determine differential crustal movement and relative sea-level change. The lithological investigations revealed re-worked Pleistocene gravels, which are believed to have acted as a type of sea-margin barrier, succeeded by marsh silts and intertidal sands. Present within these deposits thin peat seams and organic silts were also recorded (Greensmith and Tucker, 1980). Six episodes of marine transgression and five episodes of marine regression were suggested. The transgressive phases may be seen in Table 2.5

Transgressions	Date
VI	300 BP
V	1400 BP
IV	3350-2700 BP
III	4000 BP
II	7500 BP
I	8900 BP

Table 2.5 Transgressive phases for the Essex region (Greensmith & Tucker, 1980)

The study also suggested that differential subsidence along the coast between the River Blackwater and the River Thames was 4.3m during the last 4,000 years. Long & Shennan (1993) re-examined the site and subsequently confirmed these findings of differential subsidence between the two estuaries.

Long (1995) re-examined the work of Greensmith & Tucker (1980) along with more recent work by Wilkinson & Murphy (1988, 1995) and produced a relative sea-level curve based on radiocarbon dates obtained from peat deposits (Fig. 2.12). Long (1995) concluded there was insufficient evidence to prove that there was a west-east pattern of subsidence between the Thames, Essex and East Kent. Long also concluded that the rise in relative sea-level change seen at these sites appeared to be very similar, indicating that differences in the crustal movements between sites may not have affected the altitudes of the river terrace systems in this region of southern England.

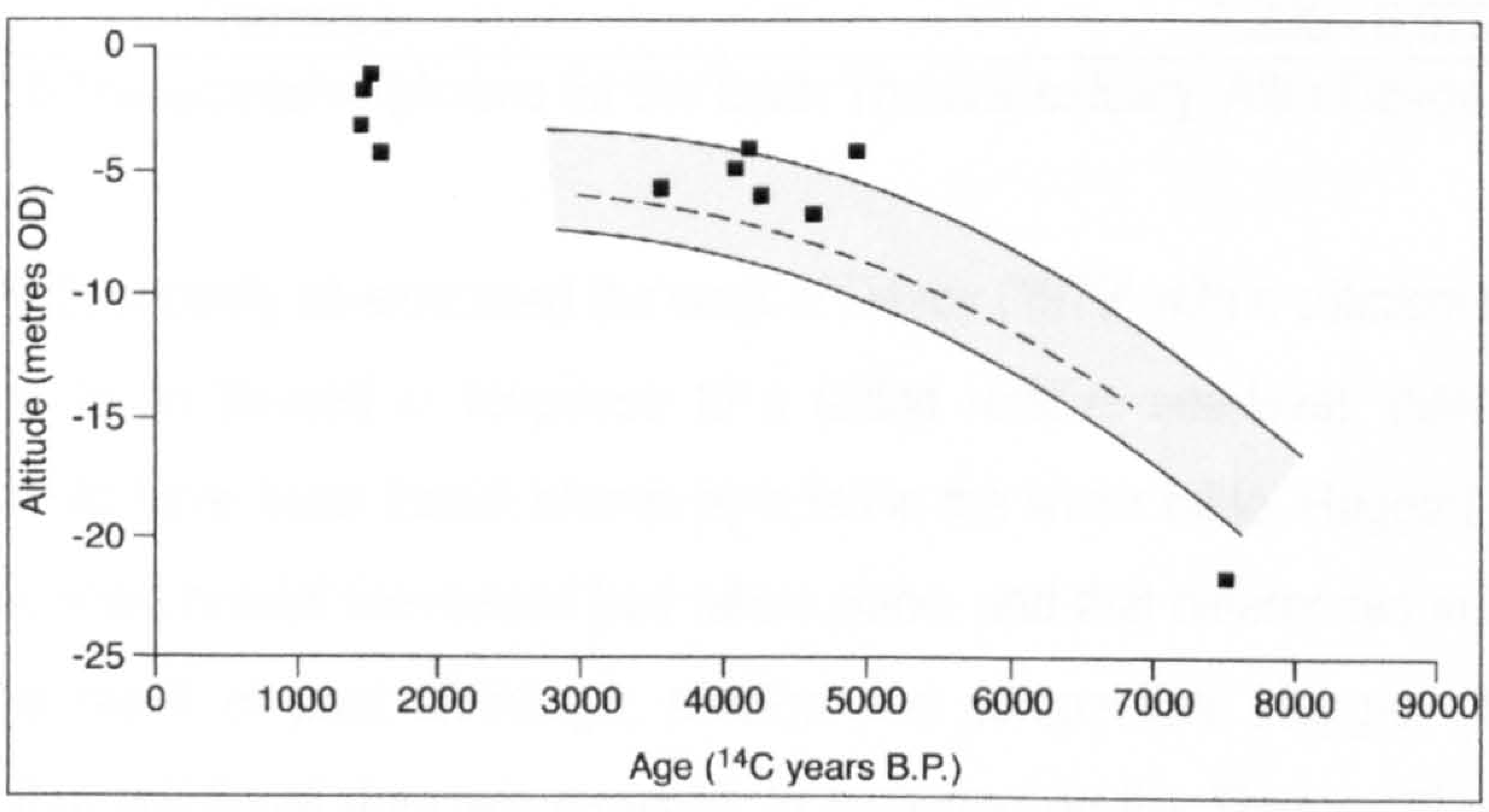

Fig. 2.12 Holocene sea-level index points, Essex. Each point represents a sea-level index point. The dashed line and the shaded area represents data from the inner Thames Estuary (Re-produced from Long, 1995 After: Devoy 1979.

Thames Estuary

Devoy (1977, 1979) produced the first comprehensive study of the lower Thames estuary, with sites at Tilbury, Crossness, Stone Marsh and Dartford Tunnel, Littlebrook, Broadness Marsh and Isle of Grain (see Fig. 2.2.11). Five transgressive and four regressive phases were identified, Thames I-V and Tilbury I-IV, respectively. The timings of these phases do not correspond well with others for the region as will become apparent (see Tables 2.5 and 2.6). Sea-level curves produced for Crossness and Tilbury revealed similar patterns (Devoy, 1979), however, the Tilbury curve (the mid-estuary) plotted 1.5–3m below the Crossness curve (the inner-estuary) (Fig. 2.13). The differences between the mid- and inner-estuaries may be attributed to a number of possible causes; compaction and consolidation of sediments, a progressive increase of tidal amplitude and freshwater discharge upstream, crustal and down-warping between Crossness and Tilbury (Devoy, 1979).

Long (1995) carried out a comparison between Essex and the Thames Estuary, concluding that the net rise in sea-level appears to be the same, but that this is not the case for other sites in southern England.

Transgressions	Date Calendar years BP
Thames V	1,750 BP
Thames IV	2,600 - / BP
Thames III	3,850 - 2,850 BP
Thames II	6,575 - 5,410 BP
Thames I	8,200 - 6,970 BP

Table 2.6 Transgressive phases for the lower Thames estuary. After Devoy (1980)

Haggart (1995) critically re-examined the work of Devoy (1979) with a criticism stating that if peat were to be formed in response to a falling relative sea-level, then additional evidence would have been found, shown by a fall in the water table. Haggart concluded that no differential crustal movement had taken place, and that differences in the curves must be the result of peat shrinkage, erosion and compaction. Haggart (1995) also concluded that additional data are required, in particular on the Thames III peat, which provided evidence of a rise, fall and subsequent rise, to elucidate the mid-Holocene rates of sea-level change.

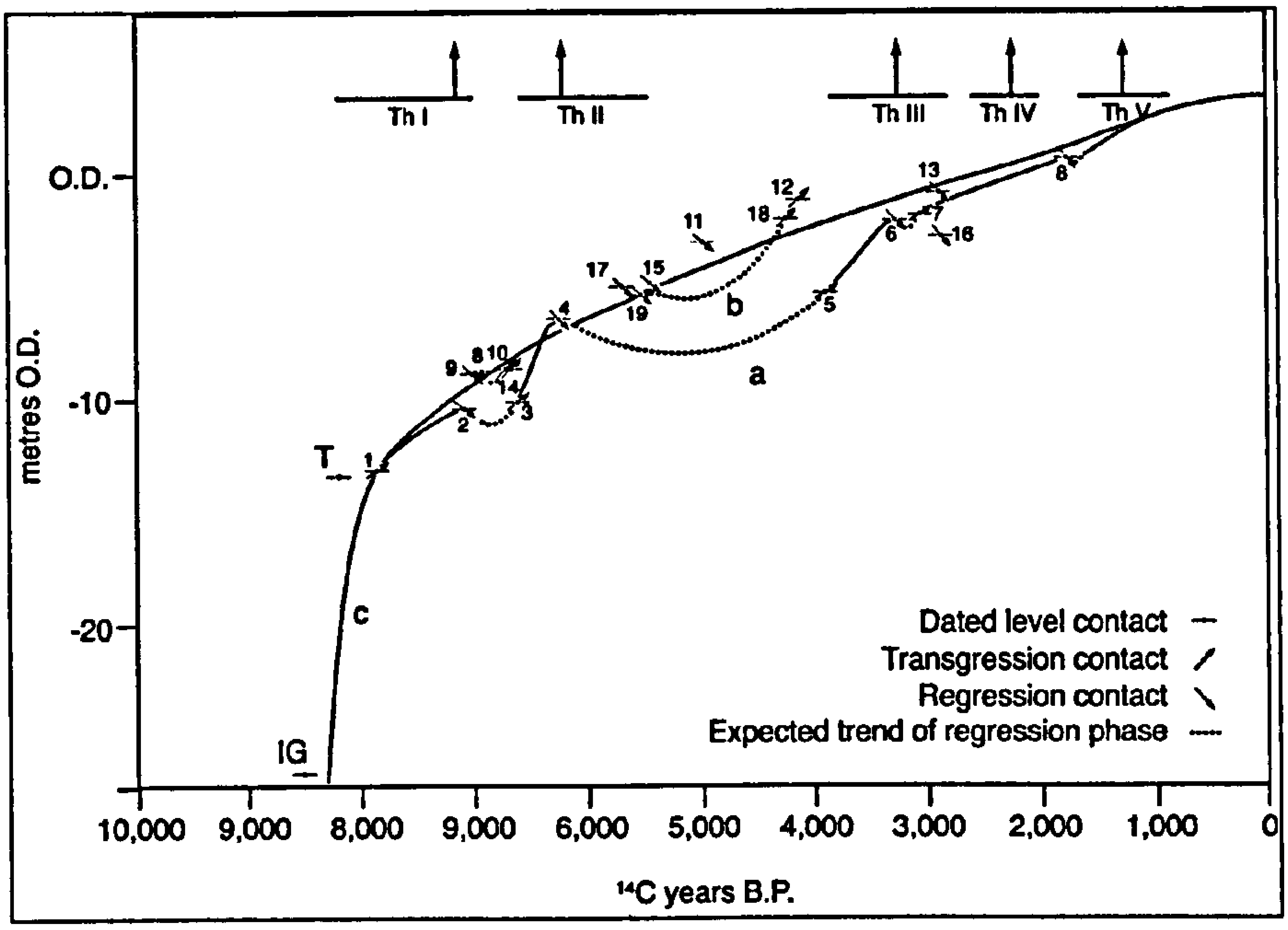

Fig. 2.13 Sea-level curve for Thames Estuary (After Devoy, 1977)
a: relative movement of MHWST at Tilbury b: relative movement of MHWST from Crossness, Stone Marsh, Dartford Tunnel and Broadness Marsh c: curve representing the mean line. ThI-V transgressions in the Thames Estuary. 1-8 Tilbury, 9-13 Stone Marsh, 14-16 Broadness marsh, 17-18 Crossness, 19 Dartford Tunnel, IG Isle of Grain

Although the research by Devoy (1979) pioneered sea-level studies in such detail, many of the interpretations have since been questioned. The impact of compaction and consolidation has been studied in more detail since this research (Allen, 2000). It has been shown that compaction and consolidation, which can often lead to underestimation of sea-level (Lambeck, 1997), could have caused the differences between the inner and outer estuaries that Devoy (1977, 1979) noted. It is likely that the mid-estuary site was subjected to more compaction and consolidation following the pattern of sediment deposition. In a valley, peat accumulates earlier and more rapidly than on the valley edges, thus leaving thicker deposits. In addition to this, the increased weight of the overlying sediments also applied a greater pressure, resulting in an increased amount of compaction and consolidation.

Kent

Godwin (1962) examined the Quaternary vegetation history of Wingham and Frogholt in eastern Kent. At Frogholt, the lowest unit recorded was 'running sand'. A peat deposit overlaid this, with blue clay above. The top unit was composed of sandy earth.

Radiocarbon dates were obtained from the peat layer dating the coarse detritus mud at 1-2cm and 20-22 cm as 2490 ± 130 BP and 2640 ± 110 BP and a piece of wood at the base of the peat (90-100cm) as 2980 ± 130 BP. Pollen analysis showed tree and shrub pollen characteristic of fen-woods. Aquatic and marsh plants were found in abundance with *Lotus* and *Anthoceros punctatus* (spores of liverwort) indicating the presence of marsh vegetation and a coastal influence. Human occupation and clearance of the land were also evident; shown by the presence of *Pteridium* and the fluctuating levels of *Corylus* in addition to high frequencies of Chenopodiaceae, *Umbelliferae, Rumex* and *Cruciferae.*

At Wingham, near Canterbury (see Fig. 2.11), the stratigraphy revealed bedrock of chalk with pebbles and flints. Blue-grey silty clay followed overlain by a light brown clay-mud. A fine detritus mud containing shell deposits followed by a coarse detritus mud, containing *Phragmites, Equisetum, Cladium* and *Menyanthes,* was then recovered. The upper unit consisted of a fine mud with clay and small chalk pebbles overlain by plough soil. Two radiocarbon dates were obtained. At a depth of 90-100 cm coarse detritus reed swamp mud dated to 2340 ± 130 BP and at 175-185 cm, fine detritus organic mud produced a date of 3105 ± 110 BP. Pollen analysis revealed fen wood and marsh vegetation to be present. A wet period was identified at 1300-1100 BP shown by *Pediastrum, Menyanthes, Potamogeton* and *Alisma* dominating. The presence of *Plantago maritima* indicated that tidal water was near. Godwin suggested that, due to the presence of *P. maritima* below + 1.8m, a marine transgression may have occurred, and concluded that the site became more waterlogged after the Neolithic A period, as a result of either increased activity in the springs from the Chalk or a rising sea-level. Few conclusive findings have been published on this site. Limited research by Wells & Waller (1999a/b) has been undertaken since, but further examination of the sea-level history at Wingham is required.

In the Lydden Valley, east of Wingham in the East Kent Fens (see Fig.2.14), Long (1991, 1992) examined the evidence for Holocene sea-level changes using seismic refraction, pollen, diatom and elemental analyses. The pattern of sea-level tendencies may be seen in Fig.2.14. Four local tendencies were recorded; 7100-6300 cal years BP (negative tendency), 6300-5900 cal years BP (positive tendency), 5900-5000 cal years BP (negative tendency) and 5000-3600 cal years BP (positive tendency). The causes of these changes were examined, ruling out differential crustal movement and local sedimentary processes such as barrier evolution, sediment in-washing and channel migration, concluding that the changes were the result of sea-level fluctuations.

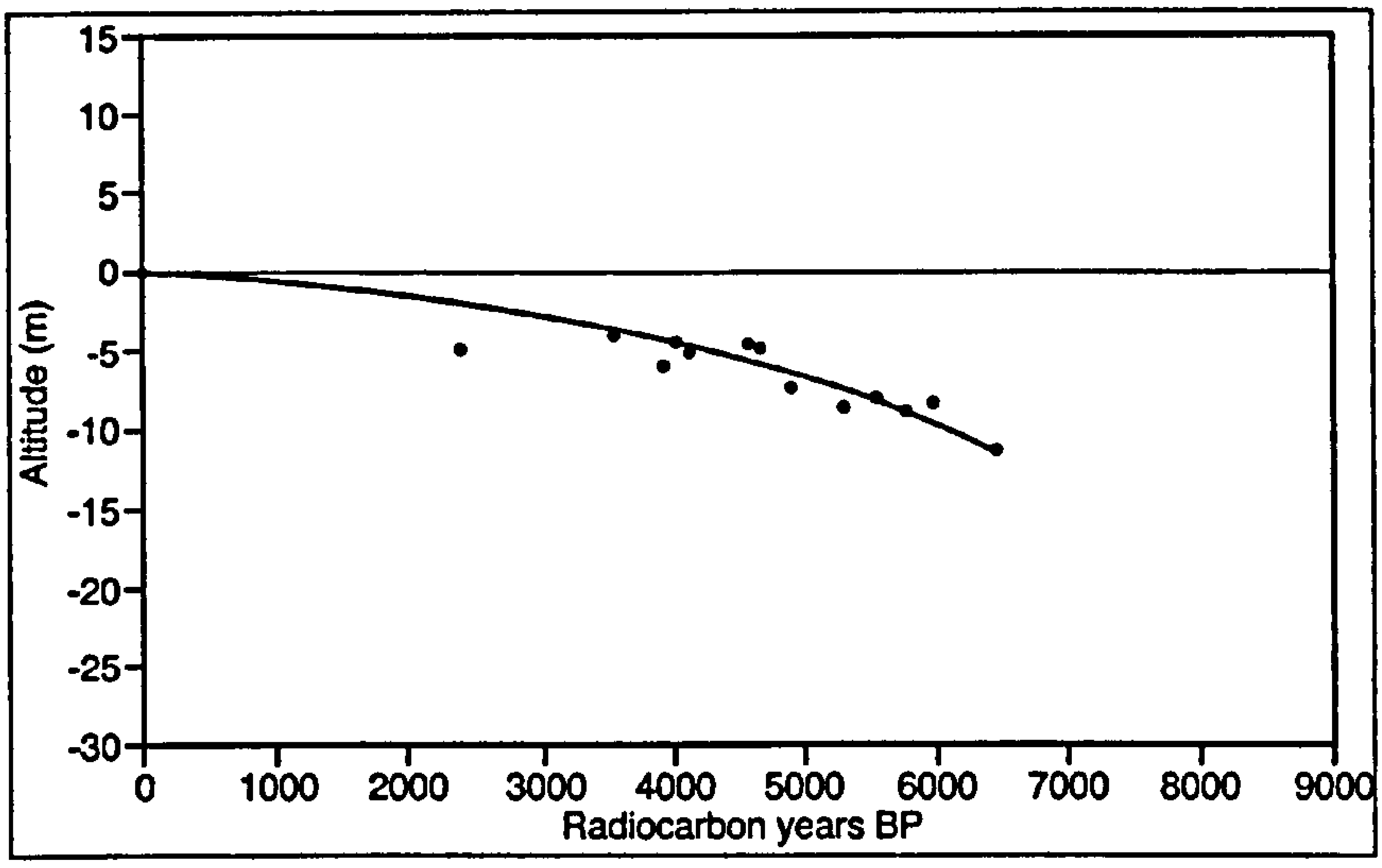

Fig.2.14 An age depth-plot for the East Kent Fens
Each point refers to a transgressive sea-level index point and
a best-fit line has been added to aid interpretation (After Long, 1991)

Long (1991) highlighted the problems associated with the sea-level tendency approach, as using transgressive and regressive contacts only shows a single point in time. The approach also requires large data sets, which is not always feasible.

Several areas of southern Kent reveal a stratigraphic record indicative of sea-level change. Romney Marsh, Brede Valley, Rother Valley and Denge Marsh have all been extensively studied. Romney Marsh, incorporating Walland Marsh and Dungeness, has been much studied. Both stratigraphical and biostratigraphical evidence has been presented (Lewis and Balchin 1940; Eddison 1983; Waller, Burrin and Marlow 1988; Long and Innes 1993; Long and Hughes, 1995; Long, *et al.* 1996; Long *et al.* 1998; Plater *et al.* 2000).

The Holocene depositional history of Romney Marsh reveals a close similarity to that of East Sussex and is therefore discussed here in greater detail than other sites from England. Lewis and Balchin (1940) carried out one of the first studies of coastal evolution in this area by performing a survey of the storm beaches at Dungeness with the aim of showing the gradual rise and fall in their height. The study discussed both crustal uplift and relative sea-level rise as possible causes of the variation in ridge heights although no clear conclusions were drawn. Studies that followed concentrated on collecting lithological, and later palaeo-ecological, evidence especially from the sediments behind the shingle barrier, in an attempt to reconstruct the sea-level record.

Eddison (1983) described Romney Marsh as showing characteristics of once being a back-barrier environment. The beaches are believed to have provided protection from the Flandrian transgression allowing the development of saltmarshes behind the barrier where salt flats had once existed. There has been considerable debate surrounding this theory and this continues today.

Waller *et al.* (1988) examined nine sites in the Brede and Rother valleys at Romney Marsh. The stratigraphy may be divided into twelve units, with a peat layer located between blue-grey clay with black and grey sands above. Pollen and plant macrofossils, along with foraminiferal analysis were used to reconstruct the sea-level history. A blue-grey sand at approximately -4m OD was shown to be an estuarine deposit and the blue-grey clay which overlies the sand is thought to have been laid down under hyposaline conditions. The main peat bed is dated to *c.* 3000 BP to *c.* 3340 BP. A sea-level index point was provided dating a marine transgression at –1.16m OD to 1830 ± 80 years BP; however, no conclusive date for the end of the peat phase was determined. Black and grey laminated sands were then recovered which suggested a low energy estuarine environment. Above this unit, the grey brown silty clays contained a pollen record characteristic of a freshwater depositional environment. Finally, grey medium sand in the upper unit was recorded at some sites, which suggested deposition occurred at the mouth of an estuary, possibly showing the existence of a palaeochannel. The study concluded that further analysis is required for the origin of this unit to be determined. The dominant cause of coastal evolution suggested by the regressive overlap which occurred at *c.* 6000 BP was still unclear and several possibilities were provided; a coastal barrier, a relative sea-level fall, a reduction in the rate of sea-level rise leading to the seaward extension of freshwater and brackish facies or an increase in sediment supply. Waller *et al.* (1988) concluded that it was not possible to reconstruct the barrier system dynamics with the available stratigraphical data and stated that more detailed studies were required.

The sea-level history for Romney Marsh has been divided into six positive tendencies and seven negative tendencies (Long & Innes, 1993). Fig.2.15 presents the relative movements in both radiocarbon years and calibrated years. The study used pollen to reconstruct the vegetation changes that had occurred throughout a peat layer that is believed to have developed between 3,700 and 2,200 BP. The pollen record showed a transition from saltmarsh pollen at the base of the peat to freshwater species. This was followed by a change to *Quercus* and then *Alnus* domination. The upper layers of the peat showed a shift back to Gramineae and saltmarsh pollen taxa, showing a rise in the water table and salinity levels. This still left unanswered questions about the influence that the coastal barrier had upon sediment deposition. The study concluded that the area experienced an increase in relative sea-level of 6m between 6000-3700 BP.

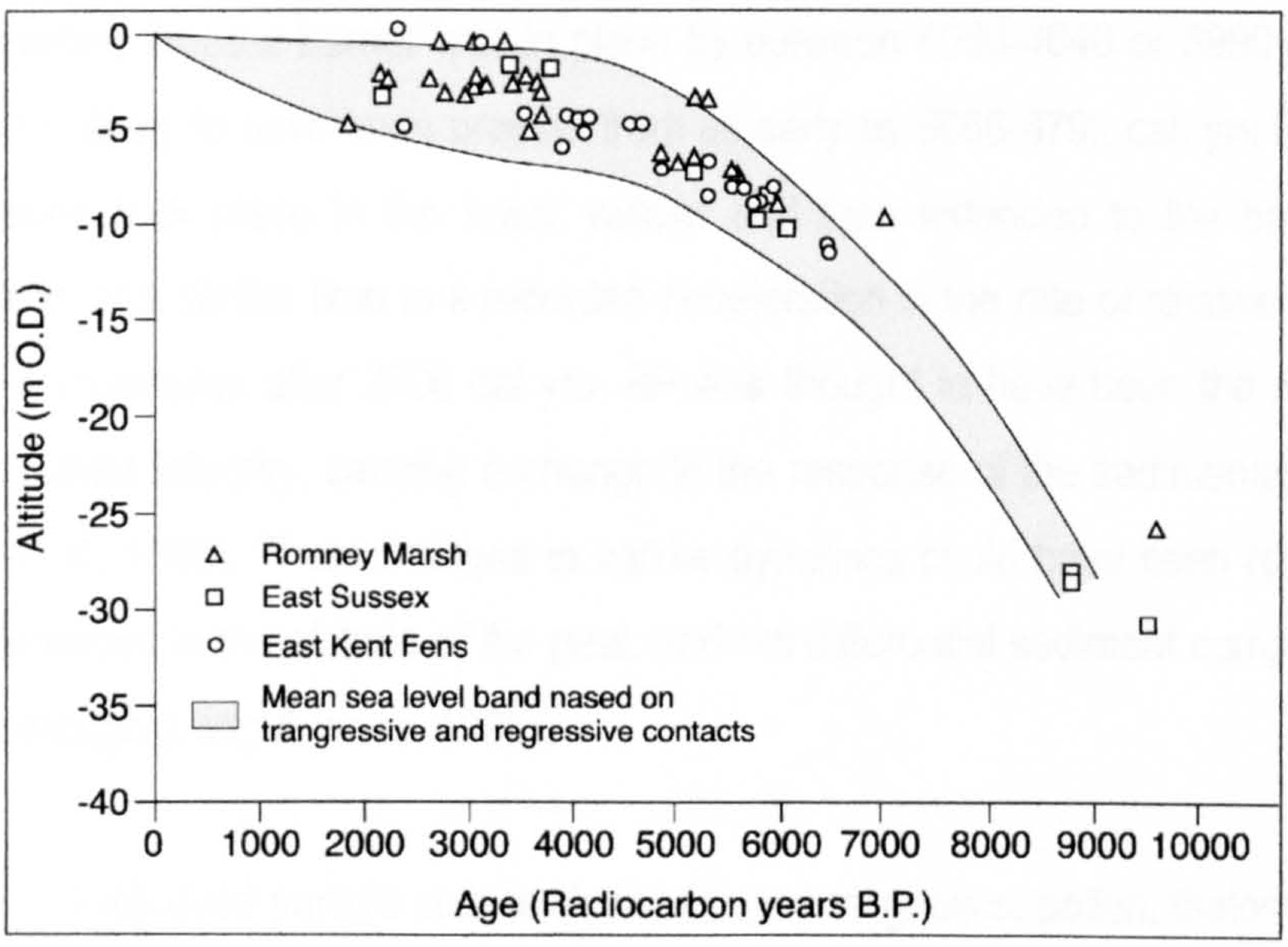

Fig 2.15 Sea-level tendencies for Romney Marsh (After: Long and Innes, 1995)

At Romney Marsh, it is not possible to discuss the pattern of relative sea-level change without describing the changes in the coastal barrier dynamics that have greatly influenced the pattern of sedimentation. Using pollen, diatom and radiocarbon data, Long & Innes (1995) tested a three-phase model of barrier development (after Orford *et al.* 1991). Romney Marsh barrier dynamics appeared to agree closely with the model suggesting three phases; initiation, stability and breakdown which at Romney occurred 6000-5000 yr BP, 5000-2000 yr BP and 2000 yr BP to present respectively.

In an attempt to determine the depositional history for the whole coastal lowland of Romney Marsh, Long & Innes (1995) moved away from the traditional method and carried out a 12-km transect across Romney Marsh. The transect revealed a single organic layer across most of Romney Marsh, however the age, altitude and sediment composition did vary.

Diatom and pollen data revealed that distinctive stratigraphical sequences could be recorded in back-, mid- and fore-marsh locations. The study also found that the differences in the altitude of the peat between the fore-marsh and mid- and back-barrier sites resulted from differential sediment compaction. Fore-marsh sites that overlay gravel will not have been subjected to as much compaction as the mid- and –back-marsh sediments that overlay silty clay. However, Spencer *et al.*, (1998) suggest an alternative proposal, stating that the barrier was in place by between 4060-4040 or 3990-3700 cal. yrs BP, but is likely to have been present from as early as 6868-6792 cal. yrs BP. Rapid peat formation took place in the lower valleys and then extended to the back-marsh environments, at a similar time to a recorded deceleration in the rate of relative sea-level rise. Marine inundation after 2900 cal yrs. BP was thought to have been the result of a change in barrier integrity, causing a change in the response of the sedimentary regime (Spencer *et al.*, 1998). Thus, changes in barrier dynamics could have been responsible for the differences in the altitude of the peat, and not differential sediment compaction as previously though (Long & Innes, 1995).

Long *et al.* (1996) used particle size analysis, mineral magnetics, pollen, diatom analysis and radiometric dating to further investigate the pattern of sedimentation at Romney. Three phases of coastal development were identified. The first identified a coarsening-upwards of the sediment after 7000 years BP interpreted as a result of a rapid rise in the relative sea-level or onshore barrier migration. The second phase was represented by a change to finer sediments. This phase was almost certainly aided by the presence of a continuous beach barrier, which protected the estuary from the sea and allowed vegetation to develop in its shadow. At this time it was suggested that the rate of relative sea-level rise was falling, allowing a stable barrier and the production of the peat sediments landward of the barrier. The final phase of coastal sedimentation from *c.* 2000 years BP to the present day, which was characterised by inundation by the sea as sea-level rose and the barrier became unstable. This study provided valuable information about the effects of coastal dynamics and barrier development when studying relative sea-level changes.

Research into the coastal evolution of Romney continued and the pattern and timing of peat development was examined (Long *et al.* 1998). The extension of the foreland westwards was shown by the spread of peat westwards. The authors suggested that this development was aided by the change in the inlet size, which was the result of a rise in relative sea-level. A fall in the rate of relative sea-level rise allowed an extension of the peat and the invasion of freshwater communities. A change back to marine conditions was then noted reflected by the shift from freshwater plant communities back to estuarine and saltmarsh sedimentation. Long *et al.* (1998) concluded that peat formation ended as a result of a change in the inlet size, which was changing to meet the increase in the amount of tidal waters resulting from a late Holocene rise in relative sea-level. The study suggested that barrier dynamics were responsible for the changes in sediment deposits and not barrier breaching as had previously been thought (Eddison, 1983). Further work was therefore undertaken to acquire knowledge about recent sea-level oscillations (Long *et al.* 1999). The stratigraphy at Romney Marsh shows that both local and regional processes have influenced the coastal development, but that local factors, which operated under periods of both high and low rates of sea-level rise, have been dominant at Romney Marsh.

The studies all show a complex relationship between barrier dynamics, sediment supply and sea-level change. The deposits recorded at Romney Marsh have developed in response to changing barrier dynamics and not a rise in sea-level breaching the barrier. However, it must be noted that that it is a combination of sea-level change and changes in barrier-dynamics that have produced such an environment. A lower rate of sea-level rise allows initiation and stability of the barrier, whereas a rising sea-level will directly contribute to its instability. Therefore it is not possible to describe the pattern of sea-level change at Romney Marsh without describing the pattern of barrier development for which there is no direct evidence.

Sussex

The sea-level history of Sussex is not as well known as it is for Kent. Previous work has relied upon lithostratigraphic evidence to reconstruct the coastal development and currently little palaeo-ecological data exist. Thus, any conclusions drawn from the following studies must be considered with some caution. The pattern of coastal evolution reveals a comparable history to that of Romney Marsh and previous work has suggested the existence of a coastal barrier during the Holocene (Shephard-Thorne, 1975; Jennings and Smyth, 1982, 1985, 1987, 1990).

The Holocene stratigraphy of Sussex has been previously documented but not in any great detail (Shephard-Thorne, 1975; Burrin, 1982). Most of the cores valley sands and gravels dominated the lowest units. Above this the characteristic blue grey clay deposits similar to that recorded at Romney Marsh can be seen, which were believed to have formed under brackish conditions resulting from barrier breakdown. Grey-black interbedded silts, silty clays and sands overlaid the clay with bluish grey or brown silty clay forming the upper layers. Of importance to note is the lack of organic layers, which have probably been overlooked in the deep unit of interbedded silts, silty clays and sands.

In order to determine the coastal evolution of Eastbourne, Jennings (1985) used pollen, foraminifera, ostracoda, mollusca and particle size at two sites, Langney Point (coastal) and Lottbridge Drove (inland). The study focused on the vegetational history and the factors responsible for the deposition of unconsolidated sediments along the coast.

Unit	**Depth**	**Composition**
Unit 4	-3.7 - +4.3	Crumbles Shingle
Unit 3	-3.7 - -24.7	Upper Minerogenic Sequence - clay, sandy clays and sand layer. Particle size analysis reveals a coarsening upwards of the sediment to the overlying shingle.
Unit 2	-24.82 - -24.7	Crumbles Peat - a thin layer of peat containing highly compacted plant macrofossils.
Unit 1	-29.1 - -24.82	Lower Minerogenic Sequence - clay and sandy clay resting upon Lower Greensand.

Table 2.7 Stratigraphy at Langney Point, Sussex. After: Jennings & Smyth (1987)

At the coastal site, Langney Point, a thin peat layer referred to as the Crumbles Peat, was found between two minerogenic layers at -24.82 - -24.7m OD. Deep drilling in this region has also exposed a layer of compact organic sediment resting on bedrock or gravel, dated to between 8,760 ± 75 BP to 9,150 ± 75 BP (Shephard-Thorne, 1975). This basal peat layer extends beyond the Crumbles Peat suggesting that freshwater conditions remained undisturbed until 8,770 ± 50 BP when estuarine conditions took over (Shephard-Thorne, 1975).

Pollen analysis at Langney Point revealed a dominance by woodland pollen throughout the early and mid-Flandrian (Jennings, 1985). Three pollen assemblage zones were identified. Zones LP1 and LP2 were dominated by *Corylus* and *Pinus*, with significant amounts of *Cyperaceae* and *Filicales* in LP1 and *Juniperus* in LP2. Jennings (1985) compared these two zones to Godwin's Boreal pollen zones. *Corylus, Quercus,* Gramineae and Chenopodiaceae dominated zone LP3, which Jennings (1985) compared to Godwin's transition from Boreal to Atlantic. However, two problems exist, firstly no *Alnus* was identified, an indicator usually found at this transition especially in wetland environments and secondly the presence of Chenopodiaceae can be indicative of either saltmarsh conditions or cultivation. In a coastal region it is also difficult to make assumptions about sea-level changes based upon these pollen records because no account of the coastal processes occurring at the time of deposition was included.

At the inland site, Lottbridge Drove, two boreholes were analysed. The deepest unit was composed of valley gravels and was overlain by silty clay, believed to be estuarine in origin, at -5.95m OD was dated to 5,000-6,000 BP, marking the earliest marine influence. A peat layer dated to be 3,390 ± 40 BP was found above the silty clay. The upper unit (Unit 4) was a clay, which Jennings described as resembling a solifluction deposit.

Unit	Depth m OD	Composition
Unit 4	+3.15 - +1.4	Upper Clay - clay containing orange mottling caused by oxidation
Unit 3	+1.4 - +0.4	Willingdon Peat - peat and brown organic clay layers, thin unit
Unit 2	+0.4 - -6.08	Lower Silty Clay - soft, fine-grained blue-grey clay or sandy clay loam
Unit 1	-6.08 - -8.19	Valley Gravels - chalk set in sand, silt and clay, highly stratified

Table 2.8 Stratigraphic record from Lottbridge Drove, Sussex. After Jennings & Smyth (1987)

Pollen analysis at Lottbridge A revealed a very different record to the coastal site. Five assemblage zones were assigned, which agreed well with the lithostratigraphic zones identified. Cyperaceae and Equisetum dominated the first zone, LD1, followed by a shift to dominance by *Alnus*, Cyperaceae, and Gramineae in the second zone LD2. The third zone, LD3 was subdivided into sub-zones, the first including *Pinus*, Gramineae, *Cyperaceae* and *Picea*, and the second including *Pinus*, Gramineae and Chenopodiaceae. Quercus, Gramineae, Chenopodiaceae and Filicales dominated zone LD4, followed by a dominance of Chenopodiaceae, Gramineae and Cyperaceae in LD5. The pollen present suggests that for most of the period saltmarsh conditions prevailed. LD3 however showed the existence of both saltwater and freshwater taxa. This agreed well with the findings of Moffat (1984, 1986) who identified a tripartite sequence at Battle, East Sussex. Moffat (1984) showed stratum 1 contained saltmarsh taxa, stratum 2 was dominated by wood peat and stratum 3 consisted of clay, silt and sand with macrofossils of reed and sedge.

The second inland site, Lottbridge Drove B, revealed a quite difference record, with a pollen record only comparable to pollen assemblage LD4 from Lottbridge Drove A. Thus, suggesting quite different depositional environments prevailed. Jennings (1985) suggested that this site was never influenced by saline conditions, concluding the stratigraphy represented a series of channels through the saltmarsh.

The Lottbridge Drove sediments led Jennings to conclude that an extensive period of estuarine conditions prevailed around Eastbourne, the onset of which was not dated due to poor pollen preservation. Freshwater conditions were believed to have inundated the area around 3,390 ± 40 BP, allowing the development of the Willingdon Peat. A regressive contact at + 1.65 m OD at Lottbridge Drove A and +0.4 m OD at Lottbridge Drove B. Jennings also described the presence of local saltmarsh channels within this unit. This phase was then interrupted by the onset of saltwater conditions, causing a disturbance in the peat layer. This was marked by a transgressive overlap at +1.92 m OD at Lottbridge Drove A and +1.37 m OD at Lottbridge Drove B. The final phase was marked by the return of freshwater conditions, shown biostratigraphically by a regressive overlap at +2.25 m OD, shifting from clay to what Jennings describes as "fill".

The study concluded that the dominant forces in the formation of the stratigraphical changes were local, not eustatic. Jennings (1985) concluded that a barrier, spit or bar, which persisted throughout the Flandrian period, had protected the Willingdon Levels.

These coastal features would have offered significant protection from the effects of eustatic oscillations and thus Jennings (1985) believed that it was not possible to state that the sediments of the area reflect the changes in sea-level. The inland organic deposit, the Willingdon Peat, was though to be topographically related. Two islands of hard Gault (clay and marl), remained present throughout the coastal changes, which influenced the pattern of sedimentation on the Levels. Therefore the study concluded that the peat was not an indicator of a marine regression. Subsequent investigations carried out, as part of this research, will challenge this conclusion.

In addition to the sea-level research undertaken, a model of coastal development for Eastbourne was presented. The model has been simplified into six stages (Jennings, 1985):

- Stage 1 (*c.*10, 000 BP, -29.0 m below mean sea-level). Dominated by Valley Gravels resulting from mass movement. Freshwater conditions prevailed with the area becoming woodland in the final period.
- Stage 2 (9,000 BP, -25 m below mean sea-level). Sedimentation during the previous stage one allowed the formation of coastal barriers, blocking tidal inlets and allowing peat formation in the shadow of the barrier.
- Stage 3 (4,000 BP) represents the most landward extent of the coastline. Estuarine conditions dominated and a significant increase in Chenopodiaceae pollen occurred.
- Stage 4 (3,400 BP) represents the formation of the Willingdon Peat and the seaward shift of the coastline. Jennings and Smyth (1987) however do not conclude this to be the result of a fall in sea-level but the result of barriers and spits forming at the coast.
- Stage 5 (800 BP) shows the coastline retreated and estuarine conditions prevailed. Pollen analysis suggests extensive forest clearance, possibly allowing sediment to become available.
- Stage 6 (present day) reveals a barrier-dominated coastline with the presence of the Crumbles Shingle at Langney Point and freshwater conditions in the Levels.

The model of coastal development and the palynological research undertaken to determine the pattern of sea-level change led Jennings to conclude that the peat deposits had not formed in response to a falling sea-level. This conclusion was not in accordance with other studies carried out in the area (Godwin, 1943; Thorley, 1971; Jones, 1981). Godwin (1943) studied the stratigraphy at Amberley Wild Brooks, Sussex, concluding that the clay represented a transgressive episode and the peat marked the end of the transgressive phase. Thorley (1971) concluded that the "transgressive peats" formed in the shadow of the coastal barrier can be used as a direct measure of sea-level change. Jones (1981) believed that sedimentation occurred behind the shingle spit that extended from Beachy Head across Pevensey. These studies and the studies at Romney Marsh discussed earlier, all concluded that back-barrier environments could be used as indicators of sea-level change though with complications. Whereas Jennings (1988) concluded that organic to inorganic transitions found in the shadow of barrier environments could not be used to provide a sea-level signal as a barrier prevents the sea from having an influence upon sedimentation.

Jennings and Smyth (1982, 1985, 1987, 1990) and Smyth and Jennings (1988) supported the notion of a stable barrier-beach acting as an obstacle to marine sediment deposition. This argument was partly upheld by Burrin (1982) on the basis of previous work in Sussex and Kent (Lewis and Balchin, 1940, Jones, 1971, Eddison, 1982). However, Burrin (1982) concluded that further analysis was required, particularly of offshore subsurface sediments, in order to determine the exact position of the barrier. Further palaeoecological data would also assist in determining whether the sediments demonstrate a fluctuating sea-level, as pollen alone can provides ambiguous information.

The vegetation history of the Brede Valley, East Sussex is already well established (Waller, 1993, 1994). Waller (1994) found the pollen record suggested an influence of changing sea-levels but attributed the complex development of the Brede Valley to changes in coastal configuration (Waller, 1993). Peat formation was found to have taken place after *c.* 6,000 BP with *Alnus* dominating the pollen record with a rise in sea-level seen after *c.* 1800 BP. Once again, this contradicted the conclusions of Jennings (1985).

The majority of studies in East Sussex have based their conclusions about the historical development of the coast upon lithostratigraphic analyses. No single study has performed both a detailed biostratigraphy and lithostratigraphy multi-proxy study of the region. Jennings (1988) and Jennings & Smyth (1982, 1985, 1987) concluded that the area of the

Willingdon Levels behind the Crumbles Shingle at Langney Point offers a unique history of development (Jennings, 1985). The existence of a barrier-beach is likely to have aided the distinct pattern of sedimentation in this region. The Pevensey Levels, although close by, are likely to offer a different history of evolution and further work is required to understand the relationship between the pattern of coastal sedimentation and sea-level change.

2.2.6 Comparison between sites in south east England

Long & Innes (1993) compared phases of marine transgressions and regressions at Romney to those found along the coast in East Sussex and the East Kent Fens. Sea-level curves for these regions have been plotted revealing a curvilinear rise in mean sea-level. Curves for Romney Marsh, East Sussex and the east Kent Fens show close similarities except for the period 5000-4000 BP when East Sussex and Romney continued to experience a rise in relative sea-level but the East Kent Fens showed a slowing down in the rate of rise. The paper stated that "there are no dated transgressive or regressive contacts from either of the three regions which are younger than *c.* 2000 BP, but since this time MSL must have risen by *c.* 1.5-2.5m in East Sussex and Romney Marsh, and by up to *c.* 5m in the East Kent Fens" (Long & Innes, 1993 p.231). The comparisons made by Long and Innes (1993) suggest that a regional pattern of sea-level change is evident along the south coast, but that local factors play an important role.

The pattern of sea-level change in south east England reveals an overall rise in mean sea-level. However, a series of marine transgressions and regressions have occurred in each estuary studied. Studies in Essex revealed six marine transgressions and five marine regressions (Greensmith & Tucker, 1980), the Thames revealed five marine transgressions and four regressions (Devoy, 1979) and Romney Marsh revealed six transgressions and seven regressions (Long & Innes, 1993). The timing of these does not correspond, although the overall pattern of a rapidly rising early-Holocene sea-level followed by a more gradual rising sea-level does, except for a continual rise in East Sussex and Romney between 5000-4000 BP.

The data in Table 2.9 reveal some similarities between the timings of marine transgressions at the sites along the south eastern coast of England. By excluding an altitudinal comparison, the problems of whether or not index points have been corrected to account for sediment compaction, whether they use the same reference water level and the production of an oscillating sea-level record are avoided. The earliest transgressive episode recorded in Essex, Sussex and the Thames Valley occurred approximately 8,500 years BP ± 300. The second event that appears to occur across the region occurred between 3,350 and 3,000 years BP and was seen in Essex, Kent and then Sussex. A third regional event can be seen approximately 2,800 years BP in Essex, Kent and the Thames, but since no data have been recorded after 3,000 years whether or not this event took place in Sussex is unknown. The implications and validity of identifying regional transgressions/regressions is discussed in Chapter Seven.

Date (C^{14} years)	**Essex**	**Kent**	**Thames** (Thames & Tilbury)	**Sussex**
500-0				
1,500-500	1,400		1,750	
2,500-1,500		2,100		
		2,200		
3,500-2,500	2,800	2,800		3,000
		3,000		
	3,350	3,200	2,600	
4,500-3,500	4,000		3,850	
5,500-4,500		5,500		5,000
6,500-5,500			6,575	
7,500-6,500				
8,500-7,500	7,500		8,200	
9,500-8,500	8,900			8,770

Table 2.9 A comparative table showing the timing of marine transgressions in south east England (After: Greensmith & Tucker, 1964; Devoy, 1979; Jennings, 1985 and Long & Innes, 1993)

The record for Kent (Long & Innes, 1993) shows the largest number of trangressive episodes. This is possibly due to the nature of the study, which included a large data set backed up by multi-proxy records, or it could be that these oscillations have been introduced in error. It is possible that negative sea-level tendencies observed at many sites simply reflect a decline in the rate of relative sea-level rise, rather than an actual fall in sea-level. When applied to an age-depth diagram these declines in relative sea-level rise are interpreted as a relative fall in sea-level, thus giving the appearance of an oscillating rising sea-level. To avoid this, many authors argue against the use of an oscillating curve (Lambeck, 1990) instead suggesting a smoothed curve is presented for smaller scale sites. Not only can errors in interpretation of the data be encountered but also errors that are inherent to the methodologies employed could result in an oscillating pattern of sea-level being observed. For example the errors incurred whilst levelling could affect the accurate use of age-depth plots. Radiocarbon dates have a 2σ error attached to them, again making the use of a single point represented on an age-depth plot subject to inaccuracy. Finally, errors due to compaction of the sediments can alter the altitude of sea-level index points on an age-depth plot. Thus, when interpreting sea-level data, great care must be taken to examine the methodologies involved in the data collection.

There is a wide range of data available for those areas believed to have been influenced by the presence of a coastal barrier system. However, many studies have been unable to determine the dominant influences and have only been able to offer possible explanations for the interaction between sea-level change and coastal development. It is possible that only those estuaries protected by barriers provide sufficient shelter to produce sea-level index points. In estuaries not protected by a barrier a considerable and prolonged fall in sea-level would be required for an organic deposit to develop. The presence of a coastal barrier offers the protection required for freshwater organic sediment to be deposited. Rapid marine inundation of an area can result in an eroded contact, with the actual sea-level index point being destroyed.

Due to the complicated nature of the sediments recorded on the south east coast of England, despite the fact that a multi-proxy approach has been employed, many of the studies conclude that further analysis is required before the evolution of the coastline can be fully determined.

2.2.7 France

Sea-level reconstructions have been undertaken on most coastlines of France, including the Channel, Atlantic and Mediterranean coasts. France has experienced a rise in mean sea-level over the last 10,000 years. However, as with the British Isles the pattern of sea-level change differs between the north and the south of the country. The Mediterranean coast has experienced significant tectonic activity compared to the northern coastlines, which has influenced the pattern of sea-level fluctuations in France (Pirazzoli, 1991).

Sea-level curves for many estuaries still do not exist and reliably dated sea-level index points are scarce. Following the conclusions of Devoy (1987) and Lambeck (1997), that sea-level curves should be constructed for small homogeneous areas, the need for further quantitative work along the French Atlantic and Channel coasts has been highlighted (Antoine, 1998). Lambeck (1997) found that Holocene sea-level change along the Channel and Atlantic coasts was not uniform due to the "response of the crust to the changing ice and water loads in late Pleistocene and Holocene time" (Lambeck, 1997 p.1). Further work is therefore required to elucidate both the pattern and rate of Holocene sea-level change.

Several major questions about the sea-level record for northern France still remain unanswered. Has the Holocene rise in sea-level been characterised by a smooth gradual rise or have there been a series of rapid oscillations? Did mean sea level ever rise above the present day mean? What influence has tectonic activity had upon the sea-level record?

The following review has been divided into two sections: the Channel coast and Atlantic coast of France. Each of these has then been sub-divided into regions to aid the description. In this section the Channel coast refers to all sites which border with the English Channel and the northern France Atlantic coast includes those estuaries which terminate into the Atlantic Ocean.

2.2.8 The Channel Coastline of France (Dunkerque – Brest)

Pas de Calais

The region of Pas de Calais extends from Dunkerque to the north bank of the River Authie (see Fig. 2.16). Many of the studies undertaken along this coast have relied upon stratigraphical data to reconstruct past sea-level changes, simply noting changes from inorganic to organic deposits (Bourdier, 1969; le Fournier, 1974; Ters *et al.*, 1980). However, one study did make use of palaeoecological data. Mariette (1971) undertook archaeological studies at several sites in northern France and produced a tentative sea-level reconstruction based on the freshwater peat layers that were recorded. It must be noted that dates were taken from archaeological remains. At Wissant, a site southwest of Calais (see Fig. 2.16), peat layers were recorded at +0.50m and +3.40m. Neolithic flints were found at 0m NGF in a peat overlying aeolian sand. These peat layers were used to indicate changes in freshwater deposition, concluding that sea-level at the late-Holocene was 3.50m below present level. At Wimereux, near Calais (Fig. 2.16), a peat layer overlying saltmarsh clay was found to contain pollen indicative of mixed oak woodland.

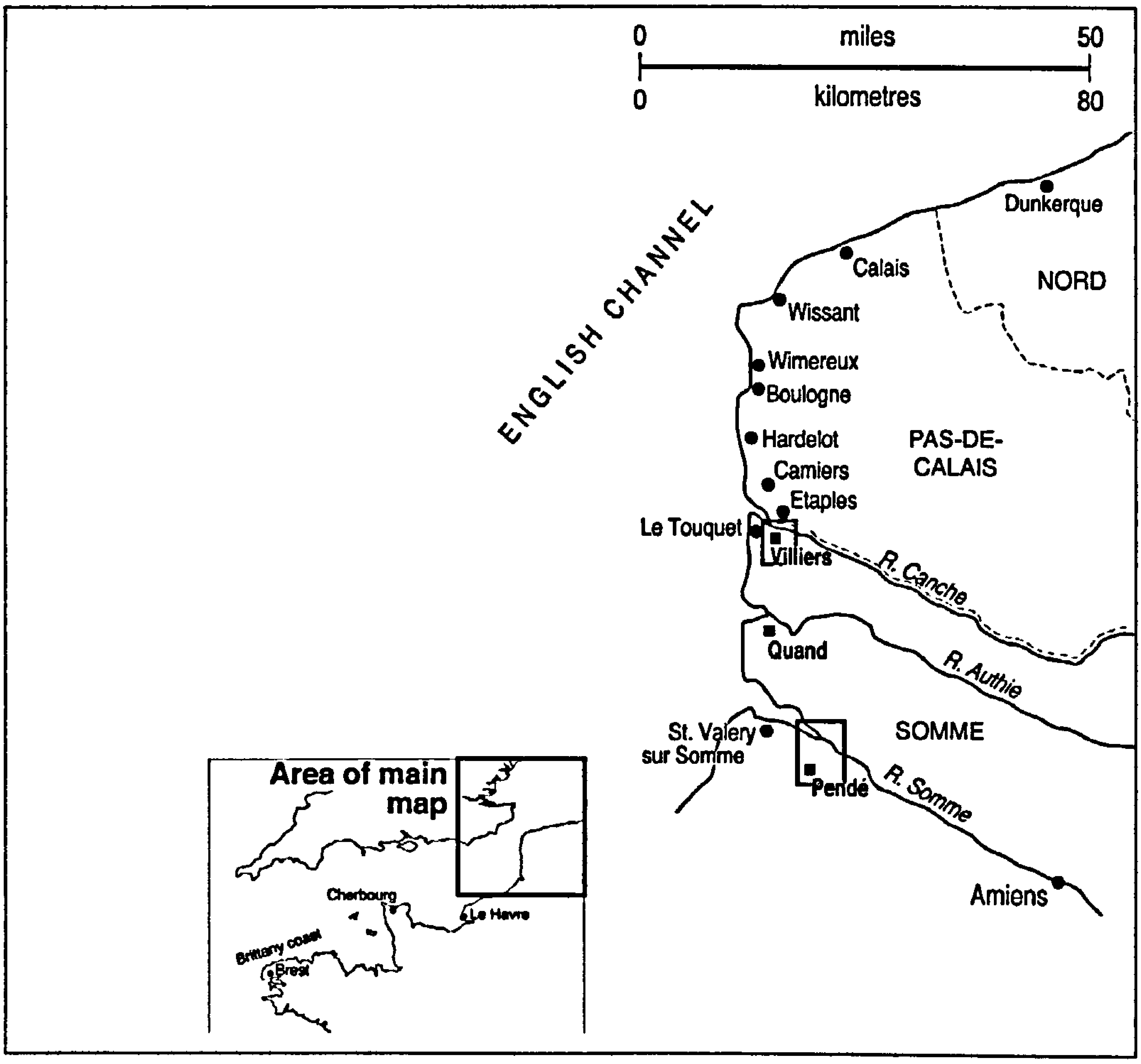

Fig. 2.16 Maps of sites discussed in France
Locations in a box and marked ▪ indicate the study sites and sites marked • refer to the sites discussed in Chapter Two.

This peat layer was used to suggest a change from a marine-brackish environment to a fully terrestrial woodland environment. Flint tiles recovered from the grey clay were dated at 2500 years BC and it was suggested that sea level was 4m below present. At the third site, Hardelot, south of Boulogne, a wood peat overlying a sand layer was radiocarbon dated at 2000 years BC. Thus the study concluded that sea-level 4000 years ago was 1.5m below the present level. The final site was at Camiers, north of the Canche (see Fig. 2.16). A compacted peat, often intercalated with grey marl containing shells, was recorded above a sand layer. A brackish clay layer recorded here was found to contain halophytic vegetation with *Scrobiculaires* and *Hydrobia* molluscs present in significant quantities. A "green layer" was also noted at this site, possibly similar to the layer recorded by Greensmith & Tucker (1973) in Essex indicating terrestrial deposition. The brackish clay was dated between 3,000 and 2,000 years BP and sea-level was stated to be 1.5m below present at that time.

The sea-level curve produced by Mariette (1971) in Fig. 2.17 shows a rapidly rising sea-level in the early Holocene followed by a slowing down period and the attainment of the present level. This is a pattern similar to that recorded along other parts of the French Channel and Atlantic coasts (Agache *et al.* 1963; Ters, 1986). However, the small-scale variations shown by Ters (1973, 1986) are not recorded due to the unsophisticated nature of the sea-level reconstruction. Mariette (1971) suggested that oscillations in the sea-level curve did occur but provided no quantitative data to support this theory. The research concluded that further work was required.

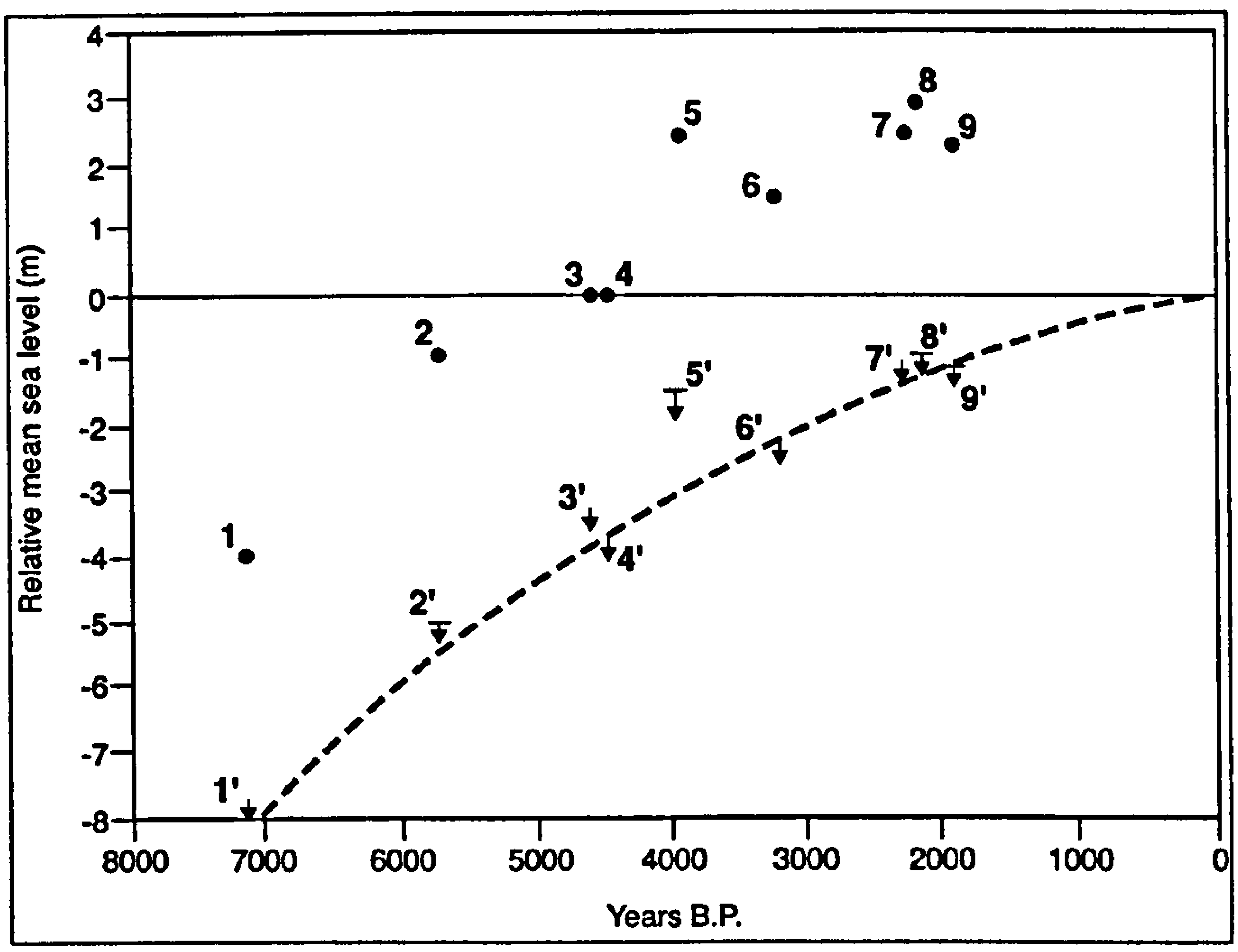

Fig. 2.17 Sea-level curve for Calais, France

Dashed line refers to a smoothed sea-level curve. The numbers refer to marine trangressions and those with an apostrophe refer to marine regressions. 1 Merlimont, 2 Camiers peat layer, 3 Wissant *Scrobiculaires* remains, 4 Wimereux, 5 Hardelot, 6 Camiers Bronze Age Site, 7 Camiers upper silt limit, 8 Camiers site, 9 Wissant Anglo-roman site (After Mariette, 1971).

Although the study provided one of the earliest sea-level studies for the region, several shortcomings must be discussed. Archaeological remains do not provide enough accurate data about the timescales involved to be used to accurately reconstruct sea-level changes. Thus reconstructions based solely upon archaeological findings must be treated with some caution.

The shells and molluscs found in the study do indicate a marine influenced depositional environment. However, molluscs are often washed-in by tides and if studied alone they can provide misleading results about past tidal levels. Therefore they would have to be recorded in their living position in order to be of use. Many authors believe that molluscs are not a good indicator of past sea-levels and that radiocarbon dates should not be obtained from such deposits (Lambeck, 1997).

Sommé *et al.* (1994) took a deep core (30m) at Watten, near the Aa valley, south of Dunkerque (see Fig. 2.16), using stratigraphy, palynology, malacology and ^{14}C dating to analyse the sediments. The authors identified four main units (see Table 2.10) within the stratigraphy. The first significant peat development began *c.*6,180 yrs BP when the sea-level was -6m N.G.F. The coarse sands found in the deposit at 180 – 0 cm depth (approximately 0 - +1.8m OD) are attributed to the return to a marine environment at *c.*1000 years BP.

Unit	Depth (m)	Description
I	14.75 – 0	Fine sand and loam sand layers inter-bedded with peat
II		Loam clays with a low calcareous content
	21.55 – 14.75	Thin compacted peat layer is present in the lower part underlying a greenish peat in which sandy laminations are observed
III	25.85 – 21.55	Loams rich in lime, increased sand content in lower part
IV	27.05 - 25.85	Clay, sands and flints with cross-bedding of sands and gravels in upper part

Table 2.10 Stratigraphy recorded in the Aa Valley, north France

Sommé *et al.* (1994)

The pollen record from the Aa Valley was divided into thirteen zones. However, these can be grouped into two major vegetation phases. Unfortunately, no dates are provided for these phases. The onset of the Holocene is marked by a transition to marshy, brackish and marine conditions, with *Corylus* present in large percentages and an increase in Chenopodiaceae. Until -18 m N.G.F estuarine conditions prevailed, when a relative fall in sea-level, shown by an increase in *Alnus* and *Tilia* pollen, can be seen. The sea is believed to have invaded the area *c.*7000 yrs B.P. at -15 m N.G.F. Estuarine conditions prevailed and the formation of a shingle barrier took place, producing the fine sand layers inter-bedded with peat seen in unit I.

The study by Sommé *et al.* (1994) allowed long-term climatic changes to be reconstructed and a useful description of Holocene vegetation change was presented, albeit at a low resolution. Some tentative suggestions about the marine influence were provided but the study did not produce a sea-level curve for the region. The presence of a basal peat layer at –18m NGF is however of great interest for sea-level reconstruction because it allows a reliable sea-level index point to be obtained. Compaction and consolidation can be allowed for since the underlying deposit (bedrock) will not have been subjected to any alteration. Unfortunately the study did not provide a radiocarbon date from this layer.

Although several studies have indirectly described the Holocene sea-level changes for the region Pas de Calais, no study has attempted to reconstruct sea-level at an estuary-sized scale, and no work has previously been undertaken at the Canche Estuary. The above studies provide useful indications about past water levels and the types of sediments encountered in the region, but by no means provide a reliable sea-level history.

The Somme Estuary

Elements of the Quaternary stratigraphy of the Somme region are well known (Ters *et al.* 1980; Buen *et al.*, 1998). However, most studies have concentrated on the river terrace system (le Fournier, 1974; Broquet & Buen, 1980). The present day marshes have been well studied (Verger, 1968) and some inferences have been made regarding the sea-level history of the region. However, the sea-level history for much of the estuary still remains unknown. The Somme estuary is bordered on its channel edge by a shingle barrier, which has allowed the development of an extensive saltmarsh system. Several studies provide palynological information on the peat deposits found in the Somme Estuary (Commont, 1910; Nilsson, 1960; Bourdier 1969) but none of these provided a comprehensive sea-level record.

The pollen record (Nilsson, 1960) showed an initial dominance by *Pinus* and *Betula* followed by a change to *Quercus, Ulmus* and *Alnus*. Chenopodiaceae has been found in association with the peat deposits in this region, suggesting the development of a saltmarsh. In the shadow of the barriers the presence of sandy-silt deposits suggests estuarine conditions prevailed. Unfortunately only palynological evidence was provided to support these theories. Radiocarbon dates from marine shells provided a date of 2440 ± 150 BP at the base of a cliff at Cap Hornu suggesting that a marine regression has taken place in the last 2500 years.

Verger (1968) provided a tentative sea-level history for the Picardie coastline using marsh sediment and vegetation chronology as the primary indicators. The chronology was divided into four main phases, the first of these being the last glaciation, when sea-level was at its lowest. The early Holocene was characterised by a rise in sea-level, reaching 30m below present level. By *c.* 7,500 years BP this level had reached -12m. The third phase, the mid-Holocene, has been subject to much debate. Verger (1968) concluded by stating that the height of the sea-level never rose above 5m N.G.F. This debate about sea-level rising above present-day level is discussed further in Chapter Seven.

A study to determine the Holocene pattern of relative sea-level changes along the Picardie coast was carried out by Agache *et al.* (1963) using stratigraphic and archaeological data (see Fig. 2.18). The curve showed that the Picardie coastline has been subject to a series of regressions interrupted by periods of stability or periods of transgression. Sea-level was seen to rise slowly between *c.* 9,000 yrs BP and *c.* 7,000 yrs BP. This was followed by a short-lived marine regression at approximately 7,000 yrs BP. A fairly sharp marine transgression was then seen to occur until *c.* 5,500 yrs BP, with a peak above present-day level being attained. An event that is still debated. This was then followed by a marine regression, which continued into the Sub-Boreal. Throughout the Sub-Boreal a fluctuating rise in sea-level can be seen, with a peak above present-day level occurring at *c.* 3,000 yrs BP. Sea-level then fell back to approximately -2m and remained stable until *c.* 1,300 yrs BP. At this time sea-level again rises above present-day level until 1,000 yrs BP when a sea-level regression occurred. The last 1,000 years to the present day is represented by a gently rising sea-level. Of particular importance is the peak above present-day level at *c.* 3000 yrs. BP, which was shown by the marine sediments overlying a peat deposit at *c.*3m NGF.

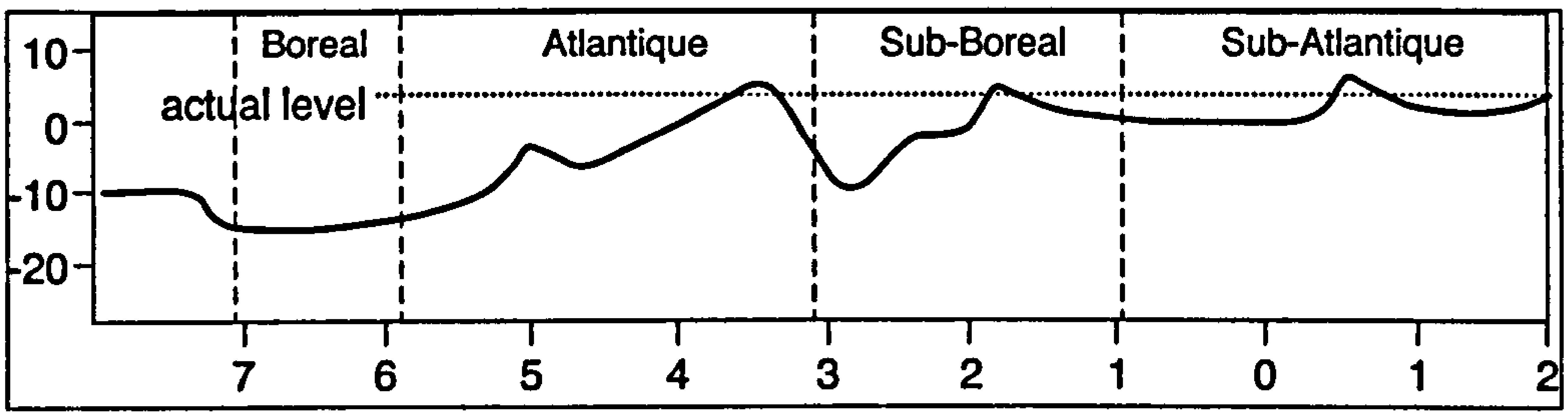

Fig 2.18 Sea-level (metres NGF) curve for the post-glacial period along the Picardie coast (Agache *et al.* 1963)

The Holocene sequence for the Somme has several published dates associated with the development of peat layers, representing two regressive periods, the first *c.*8050 ± 170 BP and the second *c.*7820 ± 170 BP (Buen and Broquet, 1980; Le Fournier, 1974). However, the most thorough study of the Holocene deposits and pattern of sea-level change was carried out by Ters *et al.* (1980). Eight episodes of marine sedimentation were recorded using stratigraphic survey supported by pollen and foraminiferal evidence. Ters *et al.* (1980) presented the depth of these phases but not any associated dates. These were described in a subsequent section, where sea-level was related to the climatic conditions. The pattern of coastal evolution and climate change were linked with the phases of sea-level change recorded, showing eight marine transgressions had taken place. The sixteen phases that Ters *et al.* (1980) noted are presented in Table 2.11. The last major transgression in the Somme estuary, was correlated with the Calais IV transgression (Ters, 1986) and is thought to have resulted in the shingle bars being breached, 2200 yrs BP.

Studies by Sommé (1994, 1998) looked at both the Pleistocene and Holocene formations along the Picardie coast, which included the Somme estuary. A series of Pleistocene shingle ridges of various heights (ranging from 9m to 19m altitude) and depth have been recorded. The sediments consisted of shingle and flints, with the sand content increasing with depth. Cores have revealed the lowest sediments at -24.75m NGF to -18.90m NGF simply to be fluvial or marine in origin, dating back to the Pleistocene, which provide little information when reconstructing past sea-level. Gravels and sands were present at the base, with sands and clays overlying them. This signalled a change in the depositional environment from fast moving water to a calm water environment, possibly suggesting the presence of an estuary or lagoon. Sommé suggested this would initially indicate that marine influence declined following a fall in relative sea-level or the onset of barrier development cutting off the area from the sea some time prior to 6500 yrs BP. The Holocene formations present in the Somme reflected the in-filling of the estuary, largely by sands and gravel. A complex pattern of peat intercalated with clayey-silt layers was evident, with the age of the upper peat estimated at 4800–2800 yrs BP and the clayey-silt dated to 6500–3000 yrs BP. This complex stratigraphy was a common feature of the mid-late Holocene deposits along this coast but has so far not been studied in any detail. This complex pattern could be indicative of a fluctuating sea-level. However, because no sea-level index points were obtained and no attempt was made to produce a sea-level curve for the estuary, the study fails to provide conclusive evidence. High-resolution palaeo-ecological analysis is therefore required on mid to late-Holocene deposits associated with the Somme estuary.

Climate phases / Sea-level variations / Coastal evolution	Description
Transgression	Rise to present level and marsh development *c.* 4m NGF
Climatic deterioration	Roman era
Transgression (Champagné)	2200 BP until present level
Regression (Belle-Ile)	2900 –2600 BP climatic deterioration and peat formation
Transgression (Camiers)	3350 BP until –3m
Regression (Argenton)	4800 – 4500 BP Peat formed
Transgression (Brétignoiles)	5100 – 5000 BP Highest sea-level
Regression (Tréompan)	6000 – 5000 peat formed *c.* 5200 BP
Transgression (Bréhec)	Until –6m Pollen record showed woody species
Regression	7300 BP reduction in foraminifera and saltmarsh at –5.15m
Temperate phase	Optimum Holocene climate – mixed oak pollen record
	10 000 – 8200 BP rapid Holocene sea-level rise (-60m to –30m) reaching –7m by 7500 BP
Third cold phase	Low sea-level
Second warm phase	Highest sea-level at Marqanterre
Second cold phase	> 38500 years
First warm phase	>38500 years
First cold phase	Postglacial / humid

Table 2.11 Holocene sea-level change in the Basse-Somme (Ters *et al.* 1980)

The Somme estuary has most recently been studied as part of the Excursion de l'Association Francaise pour l'Etude du Quaternaire (21 to 23 May 1998). The focus of the excursion lay very much on the development of the Quaternary terrace system, with little mention of sea-level changes. The estuary is characterised by a Cretaceous chalk landscape, which influences the pattern of runoff and vegetation development, determining the path of the river and the structure of the valley, in particular the Somme syncline (Antoine *et al.*, 2000). Chalk cliffs enclosed the coastal plain, which extends from Ault to Equitien. It was within this domain that the coastal marshes previously described have developed. The study provided detailed descriptions of the river terrace sediments and important information about Holocene anthropogenic influences upon the land. Unfortunately, little reference was made to Holocene sea-level changes in the estuary.

The development of the shingle barrier system at the mouth of the Somme has been well-documented (Buen *et al.*, 1998). Fig 2.19 provides a summary of the phases of barrier development. The Holocene history is broken down into five stages. The first from 8000-7000 to 5000-3000 when the sea advanced and a series of estuarine-fluvial deposits in-filled the depressions, largely dominated by silts. This was followed by the Flandrian transgression, which resulted in the erosion of the silts and the deposition of blue-grey clay. The third phase is characterised by the sea reaching the current coastline and the creation of the coastal barrier, which continued to progress northwards and deplete in the south. The estuary was subject to in-filling by fine sands at the base, with silts overlying. This ultimately led to the development of the saltmarsh system. However, the development of this system was interrupted by the permanent occupation of the land *c.*2500 years ago. The construction of the dyke system has significantly influenced the pattern of coastal evolution. The intervention of humans upon the landscape poses several problems within this area, both in terms of vegetation growth and sediment deposition. In addition, the tidal regime experienced causes complications for the occupation of the Somme valley, as the tidal range is 9–10m and the average speed of flow is 2 ms^{-1}, which can lead to flooding events. A reservoir has been constructed in an attempt to regulate the flow of seawater into the estuary. However, the area is still regularly flooded by the sea, most recently in 1990.

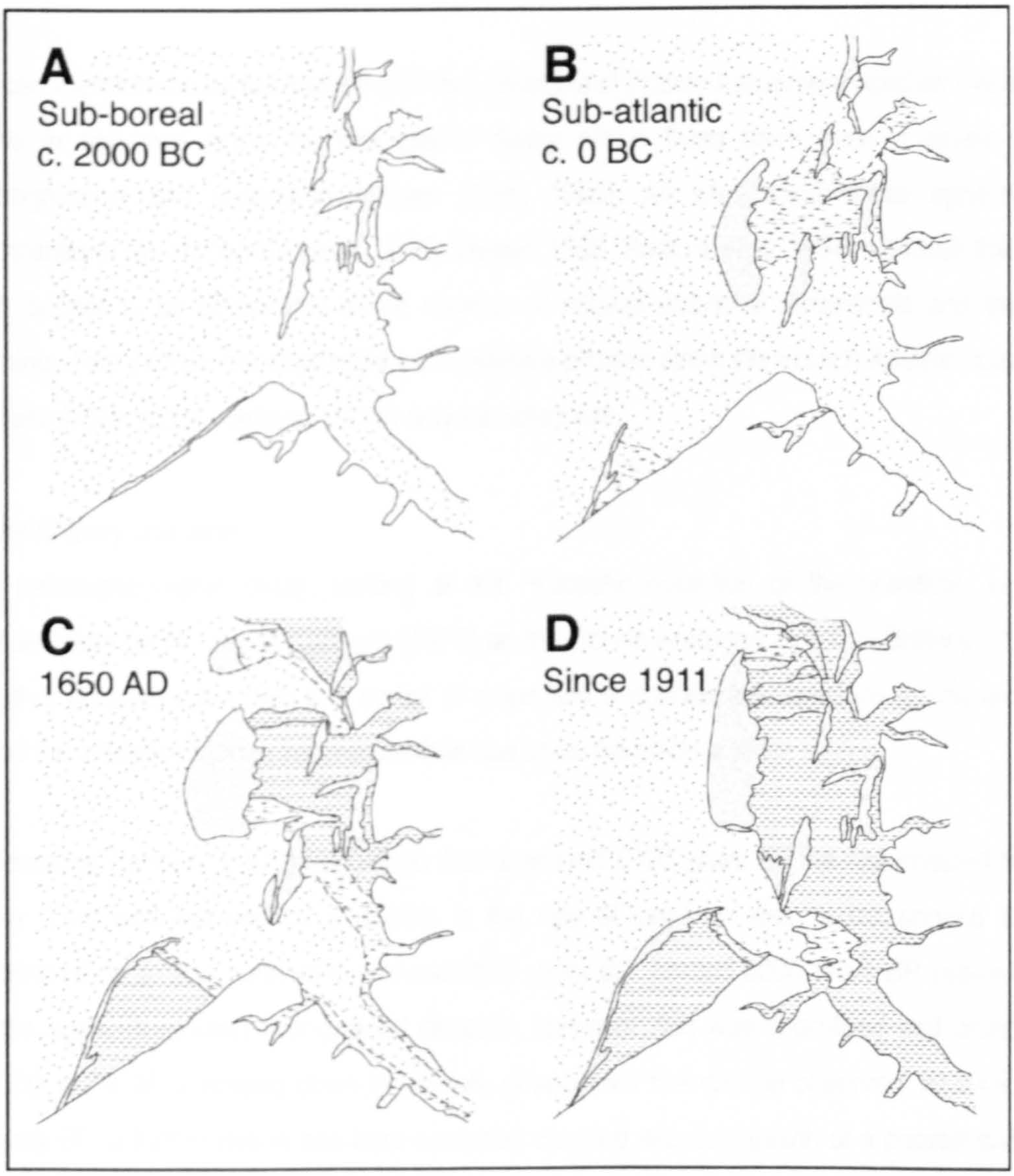

Fig 2.19 Evolution of the Somme shingle barrier system (After Buen and Broquet, 1983: In Buen *et al.* 1998) The fine dots refer to the shingle barrier, the dashed lines refer sand flats and the vegetation symbols refer to the salt marsh deposits.

The sites along the Picardie coast reveal an inconsistency in the maximum height that the sea-level attained, possibly the result of the different techniques employed in the studies. Agache *et al.* (1963) argued that the sea-level rose above the present day level on several occasions, as did Fairbridge (1961). However, Jelgersma (1966), Verger (1968) and Mariette (1971) all argued that the sea-level has never been above the present day level. In order to determine whether sea-level has risen above the present-day mean sea-level, further palaeoecological work needs to be undertaken.

It can therefore be stated that the northern coastline of France has experienced an overall rise in sea-level since the last glacial during which there have been a series of trangressive and regressive phases (Ters, 1986). All sites show these apparent fluctuations (Morzadec-Kerfourn, 1975, Verger, 1968, Sommé *et al.* 1994) although there do appear to be differences in the number of relative sea-level movements and their timing. Ters (1986) identified eight transgressive phases along the French Atlantic coast, of which Morzadec-Kerfourn (1975) only identified two.

The Brittany coastline

A palaeogeographic study, looking at the Holocene evolution of the coastline, was undertaken by Morzadec-Kerfourn (1975) on the Dol-de-Bretagne marsh in Brittany. The author presented the data in a series of maps and described the variations in sea-level and the influence human intervention has had upon the polders of the region.

Morzadec-Kerfourn (1975) suggested that at around 7000 years BP the sea invaded the bay. This was followed by a decline in the rate of sea-level rise, which caused the saltmarsh to extend northwards around 6500 years BP. Around 6000 years BP sea-level rose again, depositing finer-grained deposits. However, this was short-lived and around 5500 years BP a slowing down in the rate of sea-level rise can be observed. At *c.*4500 years BP, a further rise in sea-level occurred, coupled with the growth of a coastal sand bar. The peat, which had developed in response to a falling sea-level between 4500 and 3500 years BP, was inundated by the sea. This was then followed by the formation of an offshore bar, which subsequently protected the area from the sea. At 3000 years BP, a second coastal bar developed, allowing marsh development and human occupation. The study showed four major transgressive phases and three smaller phases (see Table 2.10). Morzadec-Kerfourn (1975) suggested the results were similar to the Dunkerque phases (Ters, 1973).

However, a comparison between Table 2.12 and Table 2.13 shows that this is not the case, since the Dunkerque phases date at 3200, 2200, 1800 and 1100 years BP, showing little similarity.

Transgressive phases	Date (years BP)
3b	2400 – 1850
2b	3000 – 2400
1b	3400 – 3000
4a	4400 – 3900
3a	5500 – 4400
2a	6500 – 5500
1a	8200 – 6500

Table 2.12 Transgressive phases in Dol-de-Bretagne, France

Phases denoted 'a' mark sharp trangressive phases and 'b' mark less sharp trangressive phases (Morzadec-Kerfourn, 1975)

Regnauld *et al.* (1996) looked at the dune system in northern Brittany using stratigraphic data. The study looked at the dune, lagoon and marsh system that has developed in response to the rise in sea-level during the Holocene. It revealed a continuous rise from -110m to the current position with three marine regressions occurring at 10000 yrs BP, 4000 yrs BP and 3000 yrs BP. The stratigraphy revealed a rise in relative sea-level as well as an increase in storm surges, shown by the presence of sand layers and shells within the marsh sediments. The data found by Regnauld *et al.* (1996) agreed closely with sea-level curves produced for that region by Guilcher and Hallégouët (1991) who redrew Morzadec-Kerfourn's (1974) curve showing an oscillating rising sea-level curve (see Fig. 2.20).

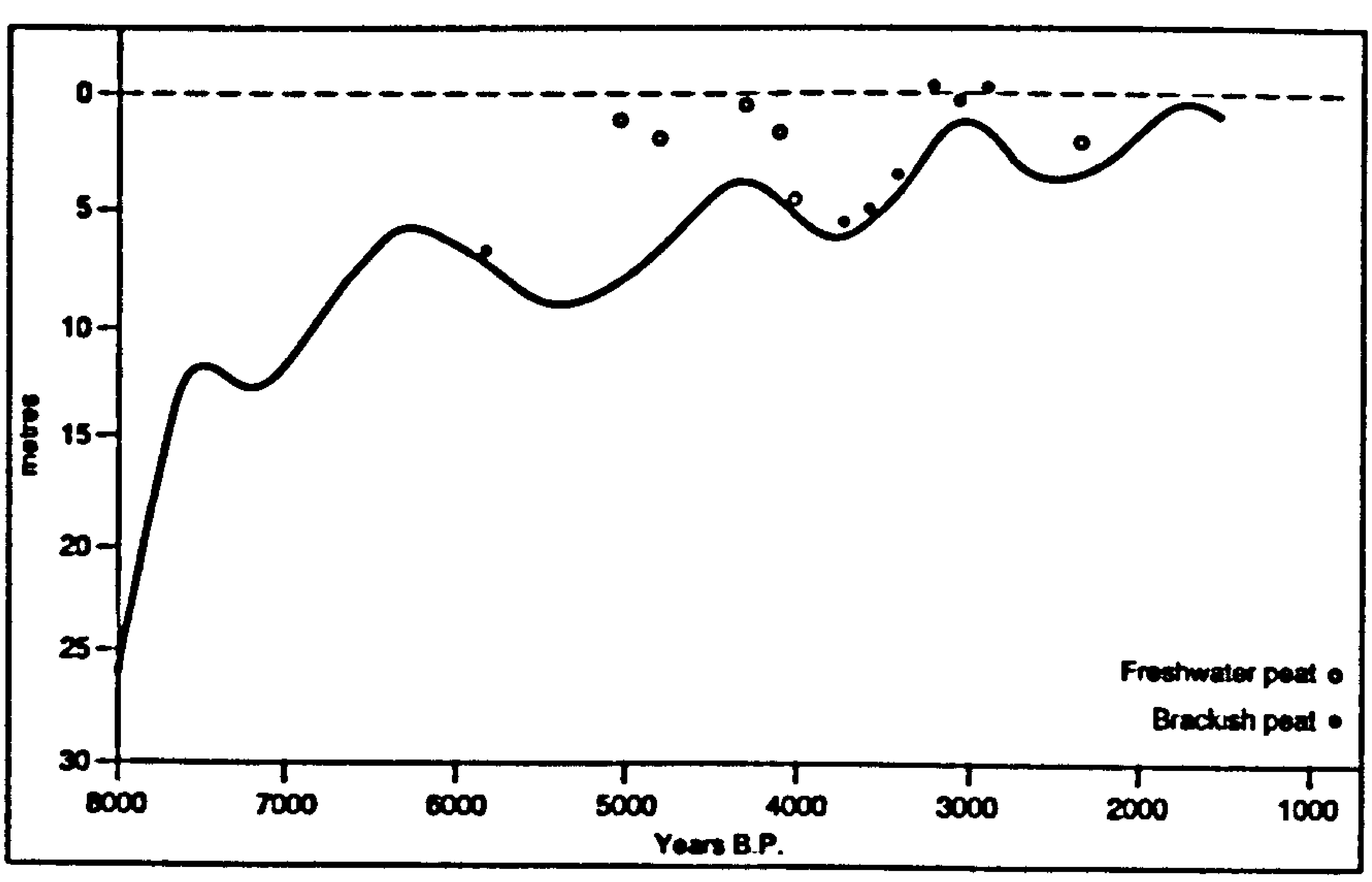

Fig. 2.20 Sea-level curve for the Brittany coast, France redrawn after Morzadec-Kerfourn (1974) After: Guilcher & Hallégouët (1991)

The Normandy coastline

Several studies have been undertaken to reconstruct the Holocene sea-level changes along the Normandy coastline, which stretches from Le Havre to Cherbourg (see Fig. 2.16 for site locations). The approach taken has placed a greater emphasis on the stratigraphy and morphology of the landscape than studies in south east England. Few studies have used multi-proxy palaeoenvironmental indicators, most of which rely on palynological data alone (Morzadec-Kerfourn, 1975).

Graindor (1959) published one of the earliest accounts of sea-level change along the Normandy coast, suggesting possible causes for the rise in sea-level during the Quaternary. These include isostasy resulting from the presence of ice masses and eustasy resulting from melting ice sheets and glaciers. Unfortunately, no sea-level curve was presented nor any data to illustrate the changes that were being described.

A peat layer recorded in Normandy (Elhai, 1963) dated a sea-level of -9.50 m NGF at 7650 yrs BP. This was followed by a rise in sea-level, shown by inter-tidal deposits and foraminifera. By the end of the Sub-Boreal *c.* 2500 yrs BP, conditions were still lower than present. However, the isostatic component was not satisfactorily determined. At 1530 years BP the sea-level is believed to have been higher than it is at present (Elhai, 1963). The final phase of development describes the period from the Middle Ages to the present day. Throughout this last phase the sea-level is believed to have been fairly stable and it is not thought to have risen above the present level. The area was largely protected due to the construction of dykes and inundation by the sea was never a threat to the land.

Hallégouët (1997) provided a good summary of the Holocene transgressions experienced in the Brittany and Normandy regions, although no new data were presented. The transgressive events documented by Morzadec-Kerfourn (1975) are discussed and compared with the southern coast of Brittany (Ters, 1973). The article point out the inconsistencies found along the Channel coast, but does highlight some similarities between the timing of the transgressive events presented by Moradec-Kerfourn (1995) and Ters (1973).

Hallégouët (1997) also noted a north to south trend in the timing of the Holocene transgression data related to glacio-isostatic readjustment and a west to east trend resulting from hydro-isostatic crustal loading. Hallégouët (1997) also discussed the possibility that the differences in the timing and pattern of the transgressive events are the result of differential compaction and consolidation of sediments, differences in the tidal regime and contamination of radiocarbon data by younger matter.

2.2.9 The northern French Atlantic coast (Brest – Bordeaux)

Further to the work on the northern Channel coastline, Ters *et al.* (1980) and Ters (1986) produced the most comprehensive summary of the variations in Holocene sea-level along the northern Atlantic coastline of French. Ters (1986) described the glacio-eustatic rise of sea-level since the last maximum glacial (17,000 to 20,000 years BP) as occurring discontinuously through a succession of transgressions and regressions. Seven major transgressions and six smaller regressions have taken place (see Table 2.13). Ters (1986) used stratigraphic data backed up with some biostratigraphic data including pollen, ostracods and foraminifera.

However, Ters (1986) noted that there was no evidence that Holocene sea-level was ever higher than the present level, which Lambeck (1997) supported. However, some authors believe there is sufficient stratigraphic evidence (Agache *et al.* 1963). This question again surrounds all the work carried out on in northern France and as yet has still not been satisfactorily answered. Additional biostratigraphic data should assist in elucidating this theroy. Ters produced a sea-level curve (see Fig 2.21) for the region, describing curves for individual regions and comparing them to variations in climate during the period. Palynological evidence was used and $^{18}O/^{16}O$ ratios were used to validate the transgressive and regressive phases.

Relative sea-level movement	Height	^{14}C date
Aunis Transgression	present level	1100 yrs BP
Wissant Regression	-1m	1300 yrs BP
Saint Firmin Transgression	0 – +0.50m	1700 yrs BP
Roman Regression	-1.50m	2000 yrs BP
Champagne Transgression	+0.50 m	2200 yrs BP
Belle Isle-en-Mer Regression	-8m	3000-2600 yrs BP
Camiers Transgression	-4m	3400-3100 yrs BP
Argenton Regression	-8m	4500 yrs BP
Bretignolles Transgression	-5m	5000 yrs BP
Treompan Regression	-12m	5700 yrs BP
Brehec Transgression	-8m	6100 yrs BP
Saint Marc Regression	-14m	7300 yrs BP
Fromentine Transgression	-7m	7500 yrs BP

Table 2.13 Holocene sea-level transgressions and regressions on the French Atlantic Coast. After Ters (1986)

The sea-level curve produced by Ters (1986) shows a highly fluctuating sea-level with two peaks above 0 m N.G.F. at approximately 2000 years BP and 1800 years BP. The relationship between the observed and predicted curves (after Mörner, 1969) can also be seen, showing general agreement in the pattern of change, although the predicted curve over-estimated the rate prior to 2000 years B.P.

In the way that many authors refer to the Thames transgressive phases and Tilbury regressive phases for south east England (Devoy, 1979), Ters (1973) published a sequence of events to characterise Calais and Dunkerque on the northern coast of France. The phases of sea-level rise and fall along the northern coast of France have been divided into two main phases, termed the Calais and Dunkerque phases (Ters, 1973). These have then been sub-divided into eight transgressions, Calais I-IV and Dunkerque 0-III. Table 2.14 illustrates the timing of the transgressive phases identified by Ters (1973, 1986). The DII stage of the Dunkerque transgression *c.* 1700 years BP, appears to be a common event noted along the northern coastal plain of France (Houthuys *et al.*, 1993). This event is often recorded at sites where the presence of a shingle bar is thought to have influenced the morphology of the coastline. These timings have been criticised by Lambeck (1997) who highlighted that many dates were not dated by radiocarbon and were simply estimates.

Transgressive phase	Date years BP
Dunkerque III	1100
Dunkerque II	1800
Dunkerque I	2200
Dunkerque 0	3200
Calais IV	4000
Calais III	5000
Calais II	6100
Calais I	7400

Table 2.14 Sea-level transgressive phases in northern France. After Ters (1973)

Lambeck (1997) compared observational and modelled data for sites along the Atlantic and Channel coasts of France. He highlighted the difference between the theories of Delibrias & Guilcher (1971), who carried out a similar study to Ters (1973) and concluded that oscillations of sea-level had occurred; and Mörner (1980) who found that there was insufficient evidence to support such oscillations. Lambeck (1997) also challenged the idea of such oscillations, stating that "...a 5m oscillation suggested by Ters (1973, 1986), requires a cyclic change in ice volume equal to about 30% of the Scandinavian ice sheet within about 1000 years or less" (Lambeck, 1997 p.2). If the model parameters used by Lambeck are correct then oscillations at the scale suggested by many authors (Agache *et al.*, 1963; Ters, 1973 and Ters *et al.* 1980) are quite improbable.

The above discussion exemplifies the need for further research. The number of sea-level studies undertaken along the French Channel coast is limited and in particular no study so far has used a multi-proxy palaeoecological approach. The key issues arising from this review are firstly, what was the pattern of mid- to late-Holocene sea-level change along the Channel coast? Secondly, did past mean sea-level ever rise above present day mean sea-level and if so what was the timing of this event and is it evident along the entire coast or limited to a single estuary? Thirdly, do small-scale estuaries exhibit the same pattern of sea-level change? Fourthly, what has the influence of barrier dynamics been upon the pattern of coastal sedimentation? Finally, is the pattern observed along the French Channel coast similar to that observed along the English Channel coast?

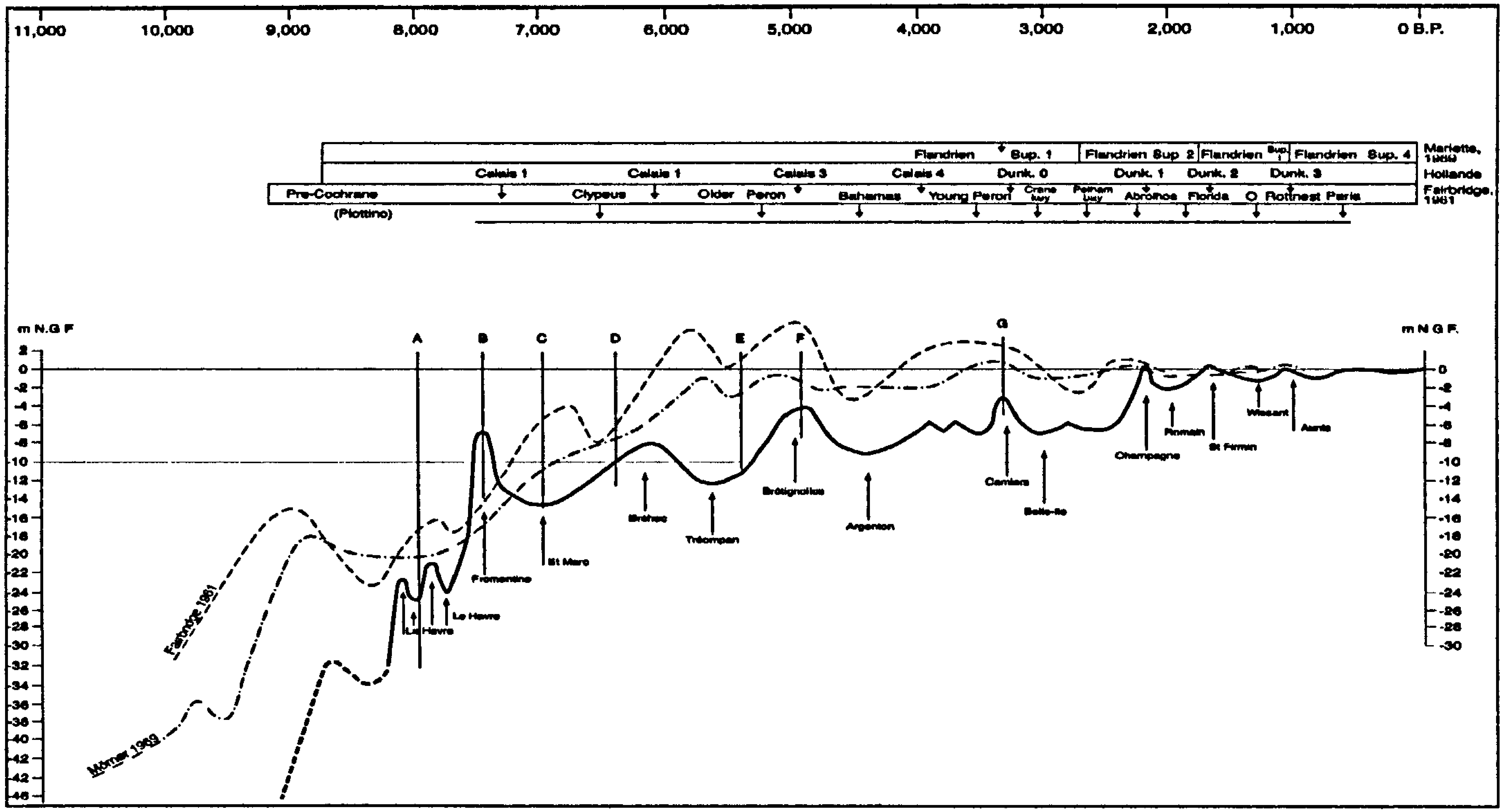

Fig 2.21 Sea-level curve for the French Atlantic coast

The solid line represents the data collected by Ters. The short dashed line shows the curve proposed by Fairbridge (1961) and the dashed line with points shows the predicted curve presented by Mörner (1969). The box above describes the various terms used to describe the transgressive phases in north west Europe (Adapted from Ters, 1986 p.208)

2.2.10 A tentative comparison between south east England and northern France

The Holocene sea-level curves that have been produced for the two regions show some similarities, which require further attention. A full discussion of the cross-channel comparison carried out in south east England and northern France as part of this research may be found in Chapter Seven.

It is evident that there has been a general pattern of relative sea-level rise over the past 10,000 years. The sites either side of the Channel show a rising sea-level curve with periods of both relative rise and relative fall being observed. The number and timing of these transgressions and regressions however, vary greatly between sites as would be expected (see Table 2.15), depending upon the local controls, such as sediment supply and tidal range. There is a debate surrounding the identification of regional transgressions/regressions, which is discussed in Chapter Seven.

It can be seen in Table 2.14 that some transgressions do correspond, but not as clearly as Delibrias & Morzadec-Kerfourn (1975) suggested. Both Essex and the French Atlantic coast experienced a transgressive phases *c.*7,500 years BP. At 5,500 Kent and the Channel coast both show a transgressive event and shortly afterwards *c.*5,000 years BP Sussex and the French Atlantic coast both experienced a transgressive event. Essex, Brittany and the French Atlantic coast all show evidence for a transgressive phase *c.*4,000 years BP, and *c.*3,000 years BP Kent, Sussex, the French Channel coast and the French Atlantic coasts all seemed to have experienced a rise in relative sea-level. The more recent events prove more difficult to correlate, since most sites lack data for the last 2,000 years. However, correlations may be made between Kent and the French Atlantic coast with a rise at *c.*2,200 years BP and between Essex and the French Channel coast *c.*1,400 years BP.

However, many of the transgressive events listed in Table 2.15 do not correspond. It must be noted at this point that only a spatial element is being discussed. This is to avoid the problems of inconsistent data collection, such as whether sediment compaction has been corrected for. One of the problems with performing such correlations is that errors or inconsistencies in the data reveal unrealistic records. For example, Sussex lacks any data for the past 3,000 years, making correlation with sites in France over this period impossible. Of particular interest to note is the frequency of oscillations seen to occur in Kent and along the French Atlantic coast (Long & Innes, 1993; Ters, 1986). A high number of transgressions between 3,200 and 2,100 years BP were documented (Long & Innes, 1993), with rises seen approximately every 200 years. This pattern is not recorded at any other sites in south east England or northern France. The amplitude and timings of such rapid oscillations has been criticised before. Delibrias & Guilcher (1971) found that data collected from the French Atlantic coast did not indicate any Holocene oscillations greater than 1m due to uncertainties in grouping sea-level data collected using different indicators. Long & Innes (1993) suggested even shorter time scales, indicating that uncertainties in the data are responsible for the oscillations. In addition to this, the errors incurred through radiocarbon dating the samples are greater than the timescales of oscillations being suggested.

It is evident that additional data are still required for many areas, including Sussex, in order to provide a more complete sea-level history, comparable to the other areas. It is also evident that if an accurate cross-channel comparison is to be made, the data collected must be consistent between the sites, in order to exclude any possibility that fluctuations are the result of the methodology employed. The importance of this was highlighted in the only study to have attempted such a comparison.

2.2.9 Conclusion

Previous work undertaken along the English and French Channel coasts suggests a rising Holocene sea-level. Several sea-level curves have been produced, many using validated sea-level index points. However, this practice is largely confined to those studies along the south east coast of England. Therefore using existing data to compare sea-level change either side of the Channel produces potentially misleading information. Few multi-proxy palaeo-ecological studies have been undertaken in France, thus the need for further research, particularly along the Channel coast, is apparent.

Several sites have been identified in an attempt to examine the sea-level history at a variety of geomorphologically different estuaries. Romney Marsh is believed to have developed behind a coastal barrier formation (Eddison 1983; Lewis and Balchin 1940; Long, *et al* 1996; Long *et al* 1998; Long and Hughes, 1995; Long and Innes 1993; Waller *et al.* 1988), as have parts of coastal Sussex (Jennings and Smyth, 1982, 1985, 1987, 1990; Jones, 1981; Smyth and Jennings, 1988; Thorley, 1971). It is also believed that the Somme and possibly the Canche estuaries developed behind a coastal barrier (Verger, 1968). The comparison between the Pevensey Levels, the Somme Estuary and the Canche Estuary should provide interesting results and may help to highlight the effect of local features upon coastal evolution when sea-level changes are occurring.

The approach to the study of sea-level change has differed considerably between England and France. At present the multi-proxy approach to studying sea-level change has not been widely practised in France. This approach to data collection should allow a greater understanding of the sea-level oscillations to be obtained, thus permitting more accurate sea-level curves to be constructed.

Date (C^{14} years)	**Essex**	**Kent**	**Thames** (Thames & Tilbury)	**Sussex**	**Brittany**	**French Channel coast**	**Atlantic coast** (Calais & Dunkerque)
0	300						
500							
1,000	1,400					1,300	1,100
						1,000	
1,500			1,750				1,800
2,000		2,200					
		2,100					
2,500	2,800	2,800	2,600				2,200
3,000	3,350	3,200		3,000		3,000	3,200
		3,000					
3,500			3,850		3,500		
4,000	4,000						4,000
4,500					4,500		
5,000				5,000			5,000
5,500		5,500				5,500	
6,000					6,000		6,100
6,500			6,575				
7,000					7,000		7,400
7,500	7,500						
8,000			8,200				
8,500	8,900			8,770			
9,000						9,000-7,000	

Table 2.15 A comparison between transgressions in south east England and northern France taken from published data (Agache *et al.* 1963; Greensmith & Tucker, 1964; Morzadec-Kerfourn, 1975; Devoy, 1979; Jennings, 1985; Ters, 1987; Long & Innes, 1993)

2.3 Geophsycially modelled data

2.3.1 North west Europe

The aim of this section is to provide an overview of the main studies that have attempted to compare observed data with geophysically modelled data for the sites which have been discussed in section 2.2 above. Although previous work is available for most sites, in some instances no relevant research could be found and thus gaps in the description may exist. This section does not provide any comparisons for the study sites, since these are discussed in detail in Chapter Eight.

The geophysical models of relative sea-level change developed for the Dutch coastline (Lambeck *et al.* 1990) provide the following predictions and show the comparisons made with observed data (Fig. 2.22). It can be seen that the model predictions and sea-level observations for the last 5000 years at Groningen, Netherlands correspond well (Fig. 2.22 Lambeck, 1990). However, subsequent research has shown that the impact of short-term, high rates of tectonic activity upon the Dutch coast complicates matters.

Lambeck *et al.* (1998) covered the whole Scandinavian region examining observed versus predicted sea-levels for Norway, Sweden, Finland and Denmark. Fig. 2.23 shows a summary of these results. The patterns of relative sea-level changes between the regions appear to vary greatly. Andoya, northern Norway showed a steeply falling sea-level between 20,000 and 10,000 years BP followed by a fall below zero at 10,000 years BP. Between 10,000 and 7,000 years BP a rise in sea-level can be seen, but this did not continue and was followed by a steadily falling sea-level over the last 5,000 years. Oslofjord in southern Norway also showed a falling sea-level but no fluctuations and no drop below zero. On the west coast however, the site at Jæren shows a highly fluctuating sea-level dropping below zero regularly between 13,000 and 7,000 years ago. The last 5,000 years is however once again characterised by a steadily falling sea-level. Bjugn Trondheimsfjord, western Norway, too revealed a falling Holocene sea-level, and a clear fall for the last 5,000 years. The two areas in Finland, Oulu and south western Finland, also showed a falling sea-level over the past 10,000 years, as did the site in Sweden, Angemanälven. In contrast however the sites furthest south, Store Bælt, Denmark and the curve for the Southern North Sea both showed a rising relative sea-level for the past 10,000 years, which never rose above zero.

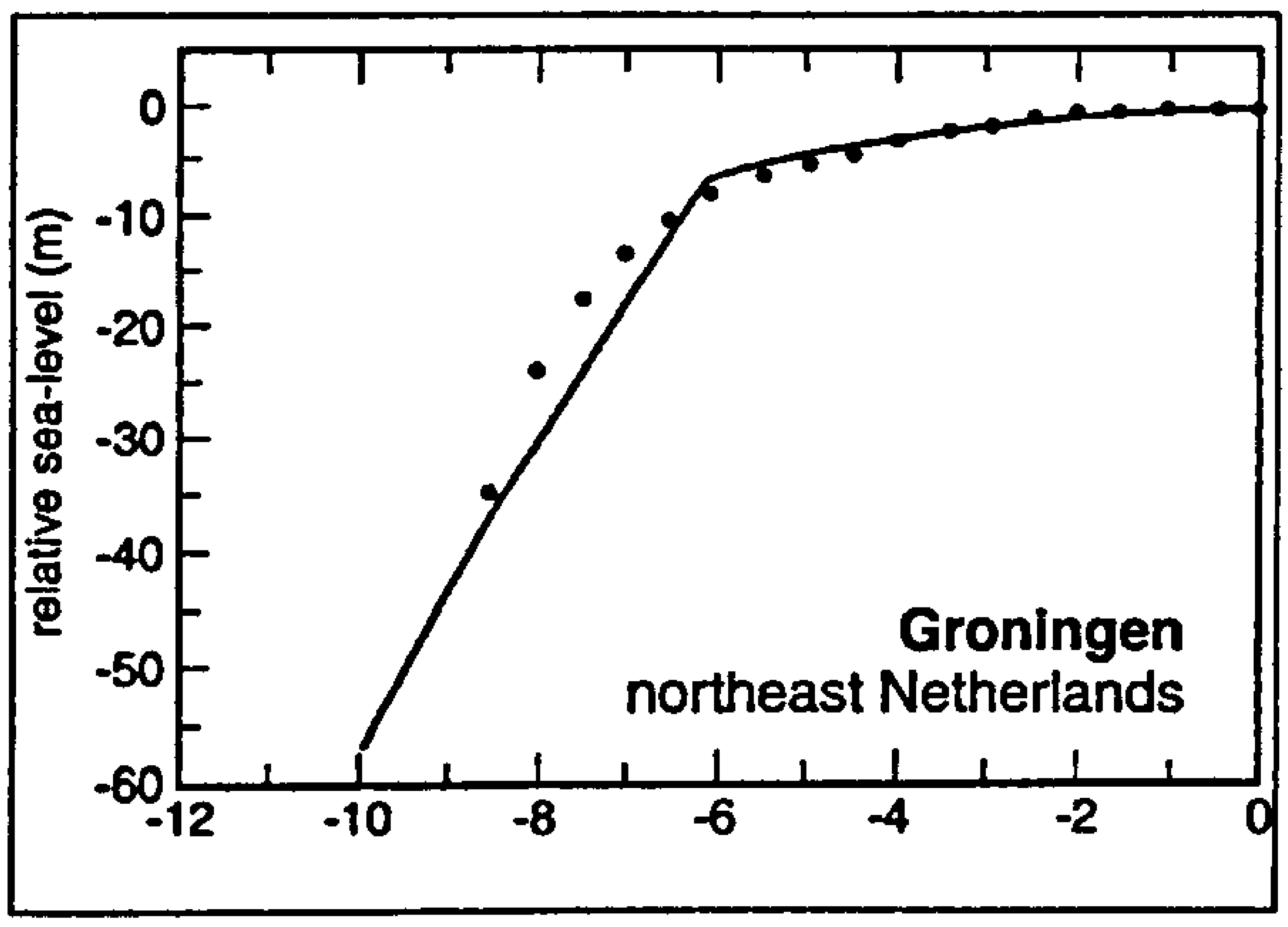

Fig. 2.22 Observational data (•) versus predicted (—) data for relative sea-level change, Groningen, Netherlands. After Lambeck *et al.* (1990)

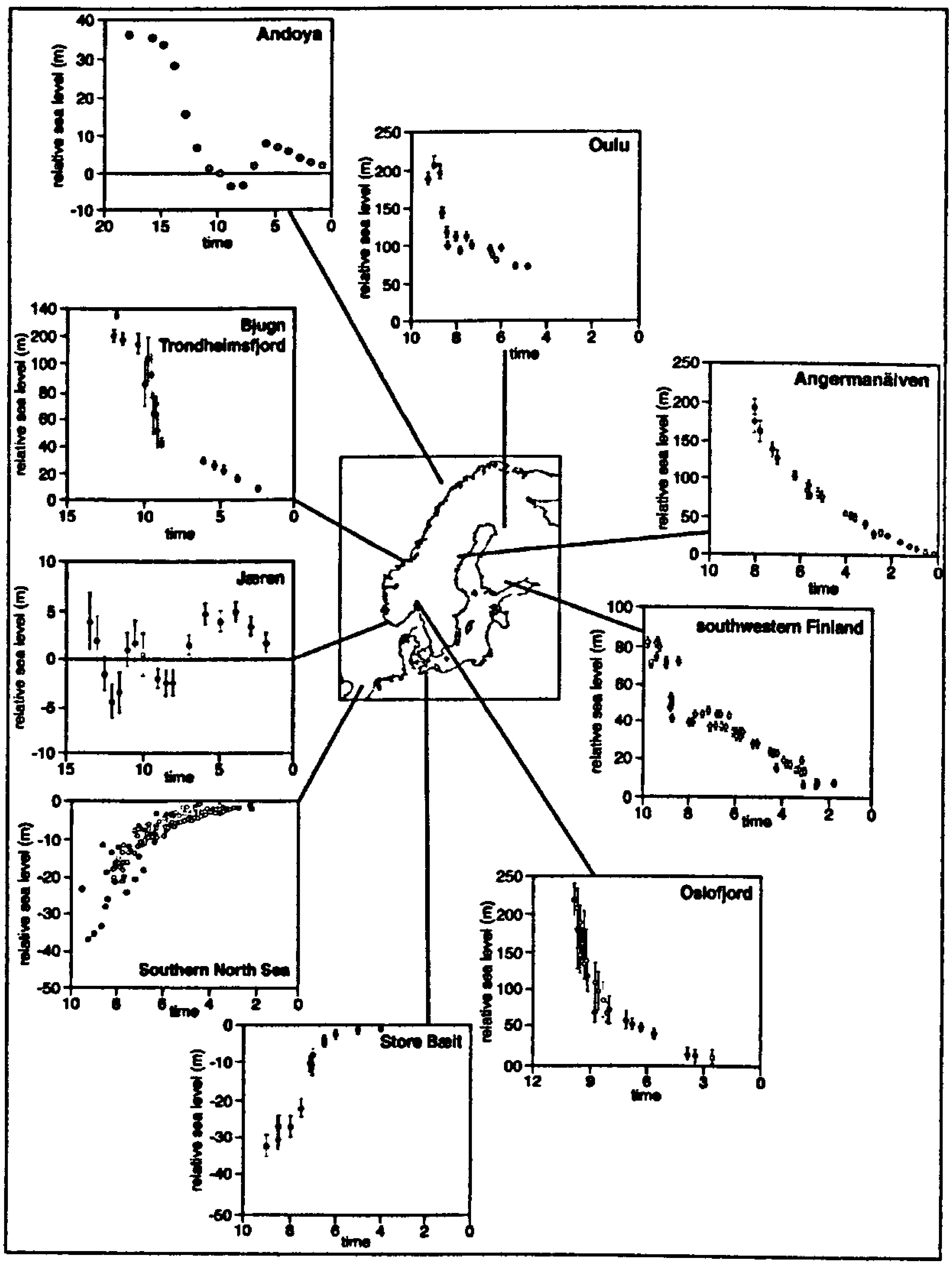

Fig.2.23 Sea-level change in Scandinavia (After Lambeck *et al.* 1998)

2.3.2 British Isles

Scotland

Lambeck (1995) produced observed versus predicted sea-level curves for three areas of Scotland, the Firth of Tay, the Firth River and Inverness (Fig. 2.24a-c). There was a very close similarity between the observed and predicted data at each site, but for the early part of the Holocene the model tended to under predict relative sea-level. It can be seen that throughout the mid-Holocene there was a very close agreement between the data sets, but towards the late-Holocene the model once again under predicted relative sea-level.

Ireland

The observed rate of relative sea-level change in north west Ireland has been compared with those predicted by Lambeck (1991). Shaw & Carter (1994) revealed a close agreement between the observed and predicted data and concluded that recent isostatic rebound models were consistent with this finding. In northeast Ireland when comparing Carter's (1992) sea-level index points with the predicted model (Lambeck, 1991) the paper concluded that a good fit was found. However, the evidence for higher, earlier shorelines was not predicted by the model, therefore contradicting this conclusion. Further modelling work (Lambeck, 1996) produced a comprehensive study of the pattern and timing of sea-level change for Ireland and the Irish Sea, showing the pattern is controlled by the isostatic rebound following the deglaciation of the British Isles. This was in agreement with the empirical findings of Carter *et al.* (1989). The Lateglacial highstands observed by Carter *et al.* (1989) in north eastern Ireland, also appeared in the model predictions (Lambeck, 1996). Fig. 2.25 below shows the observed versus predicted pattern of sea-level changes for a) Donegal, north western Ireland and b) Cork, southern Ireland. The curves clearly show that the peak above zero was not experienced in the south and that the north western site shows a recent decreased rate of sea-level rise as shown by Carter *et al.*(1989). These studies not only revealed the differences observed between sites, but also highlighted the disagreements between data types.

Northern England

Shennan *et al.*, (2000) produced a comprehensive comparison between the observed and predicted relative sea-level curves for four sites in northern England; Northumberland, Tees Estuary, Humber Estuary and Lincolnshire Marshes, based on the work of several authors (Fig. 2.26). Once again it can be seen that the two data sets showed an amazing similarity, but the model tended to slightly under predict the altitude of relative sea-level. The Lincolnshire Marshes and the Humber Estuary showed the closest agreement, with many of the observed data points falling on the predicted sea-level curve.

South west England and Wales

These two regions have been grouped together because one of the sites encompasses both south Wales and south west England. Unfortunately, no published work exists for the region of north Wales.

Fig. 2.27 shows the observed versus predicted data for Bridgwater Bay and Cardigan Bay (Lambeck, 1995). Once again it can be seen that the two data sets are extremely similar. At Bridgwater Bay, most of the observed data points actually lie on the predicted sea-level curve, throughout the last 10,000 years. The data for Cardigan Bay also shows a very close match, however once again the modelled data appears to under predict the relative sea-level compared with the observed data.

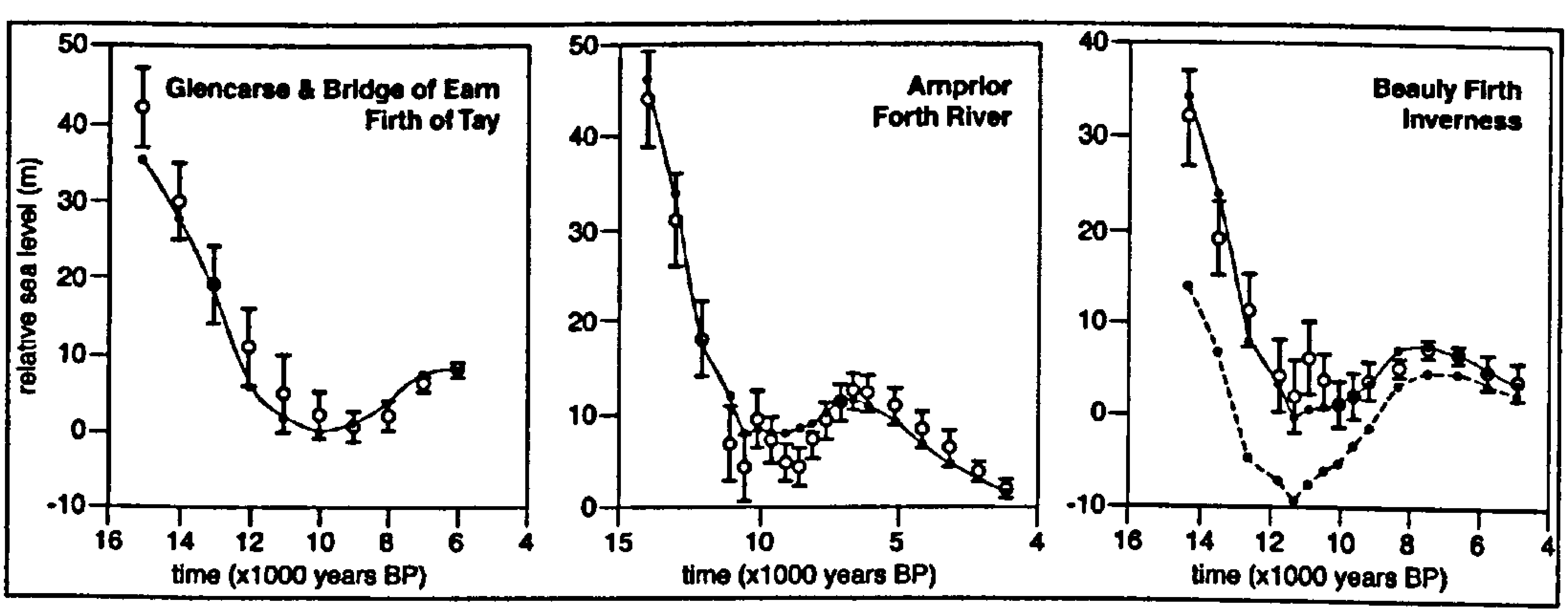

Fig. 2.24a-c Observed versus predicted data from three sites in Scotland (After Lambeck, 1995)

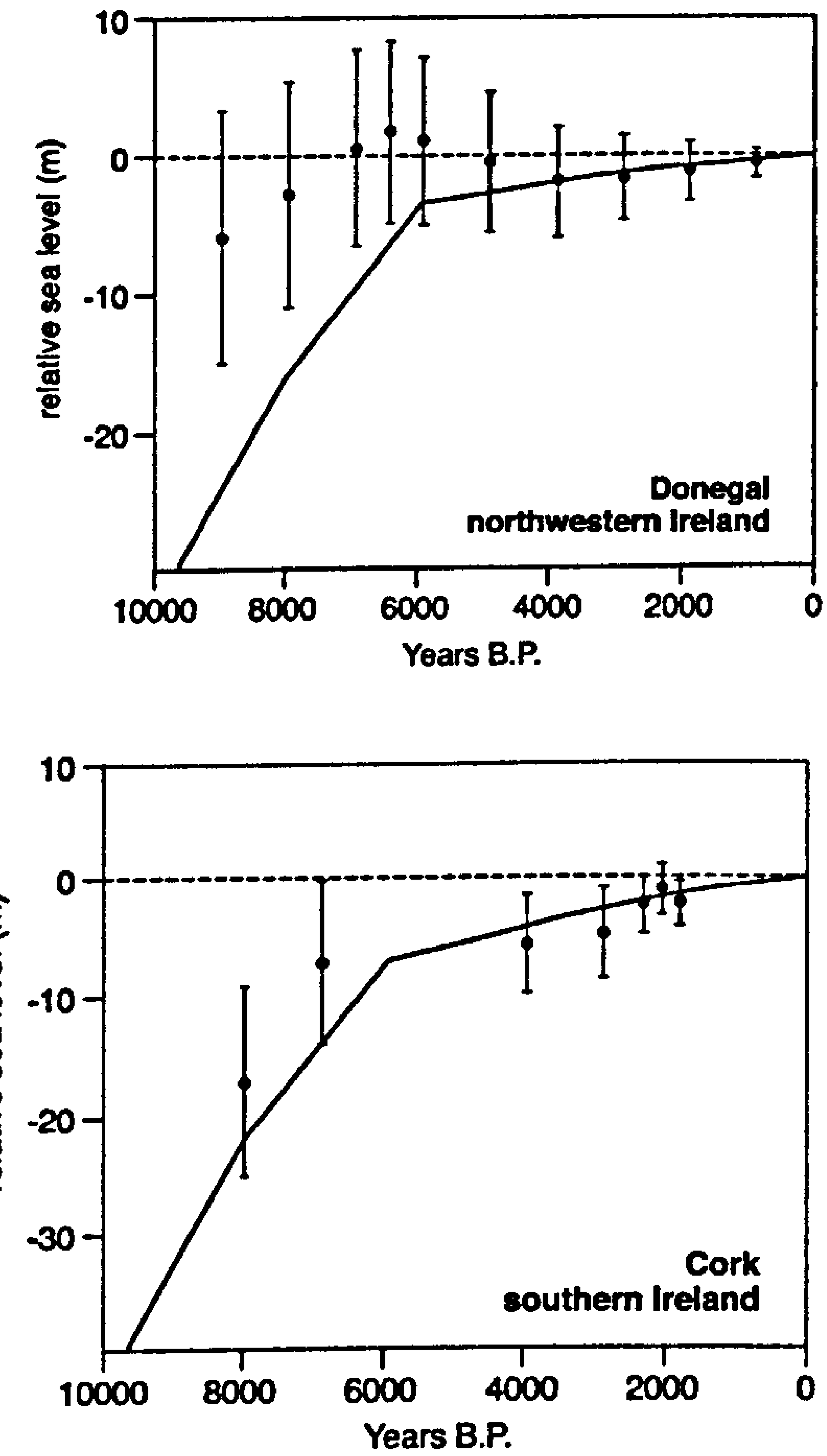

Fig. 2.25 Sea-level curves for a) Donegal, north western Ireland and b) Cork, southern Ireland. After: Lambeck (1996)

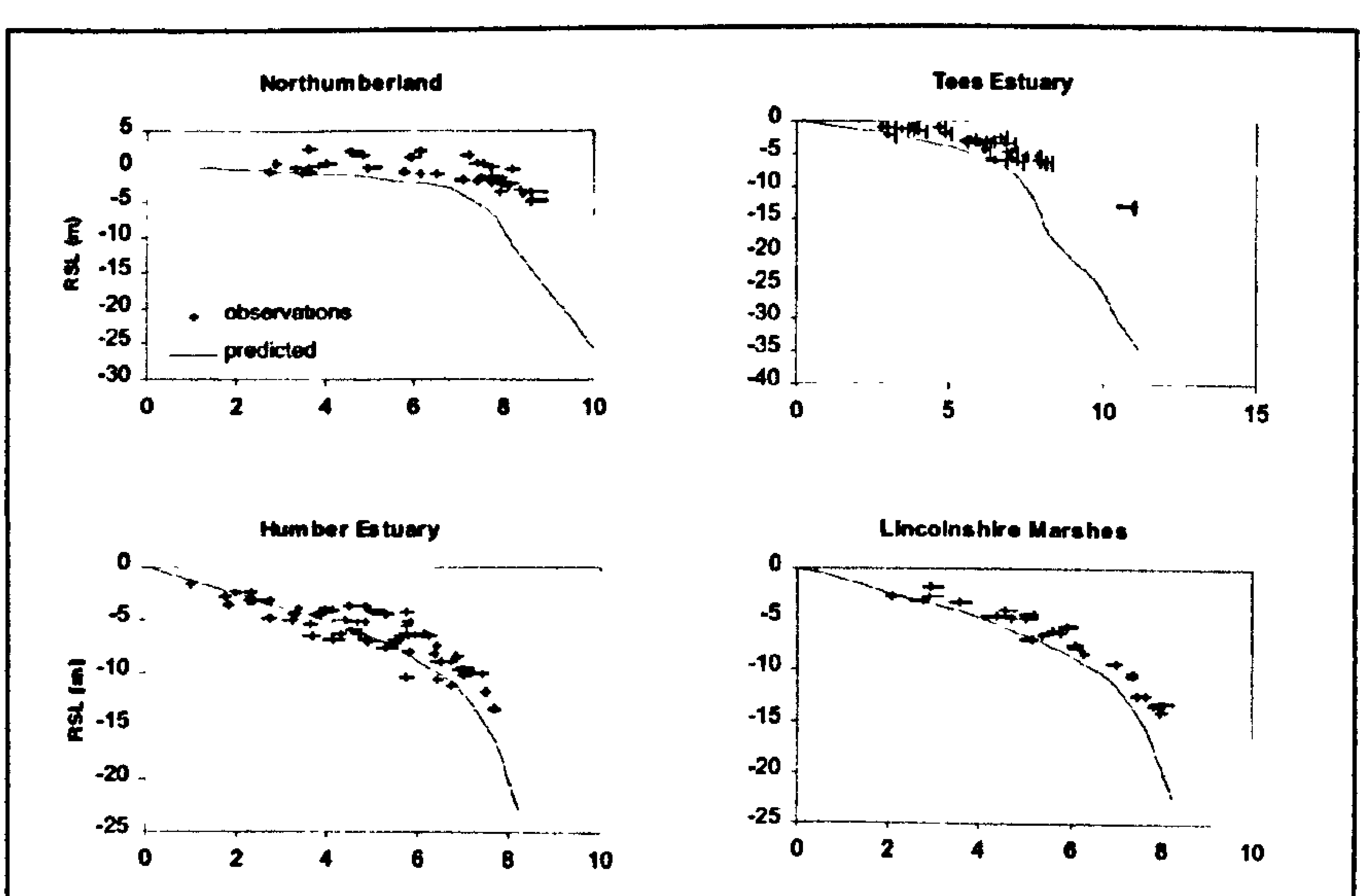

Fig. 2.26 Observed versus predicted data for four sites in North England (After Shennan *et al.*, 2000a)

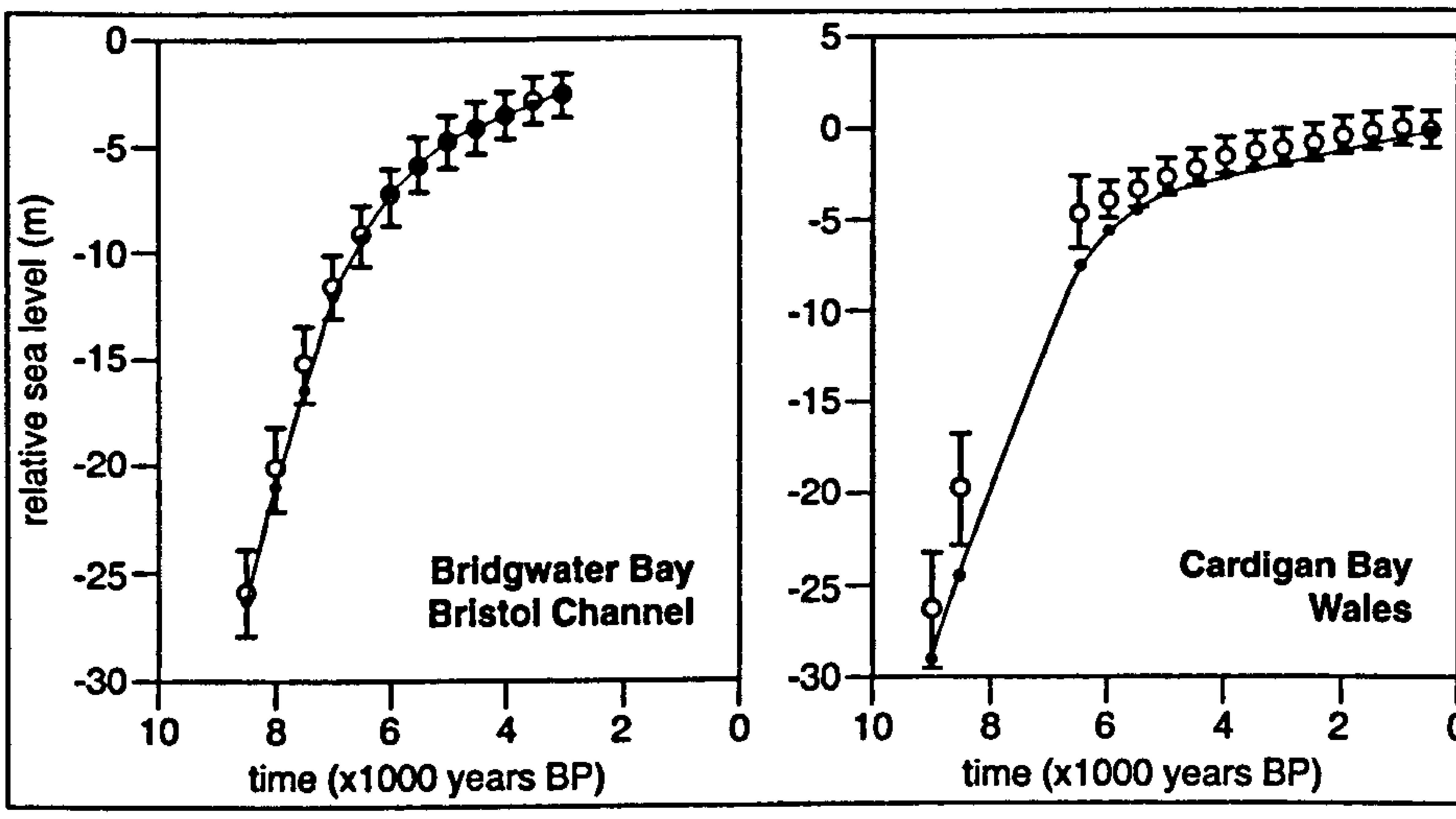

Fig. 2.27 Observed versus predicted relative sea-level for Bridgwater Bay, Bristol Channel and Cardigan Bay, Wales (After Lambeck, 1995).

South east England

Figs. 2.28 and 2.29 present the observed data plotted against the predicted data for sites in south east England (excluding the study sites). The first difference to note is that for the Fenland the model tends to over-predict the relative sea-level during the mid- to late-Holocene period. This could be due to the large spread of observed data that has been collected in the Fenland. This is an area that has been particularly affected by the presence of coastal barriers, which could have affected the observed data.

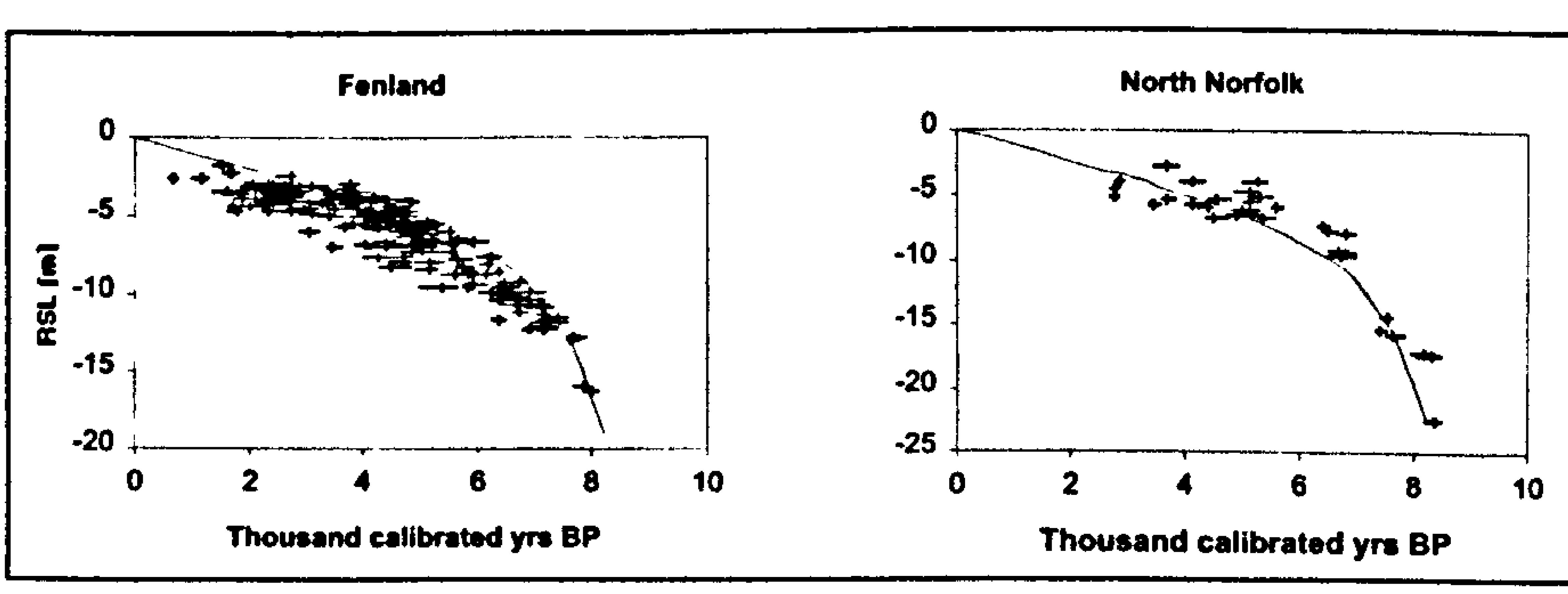

Fig. 2.28 Observed versus predicted data for south east England (After Shennan *et al.*, 2000a)

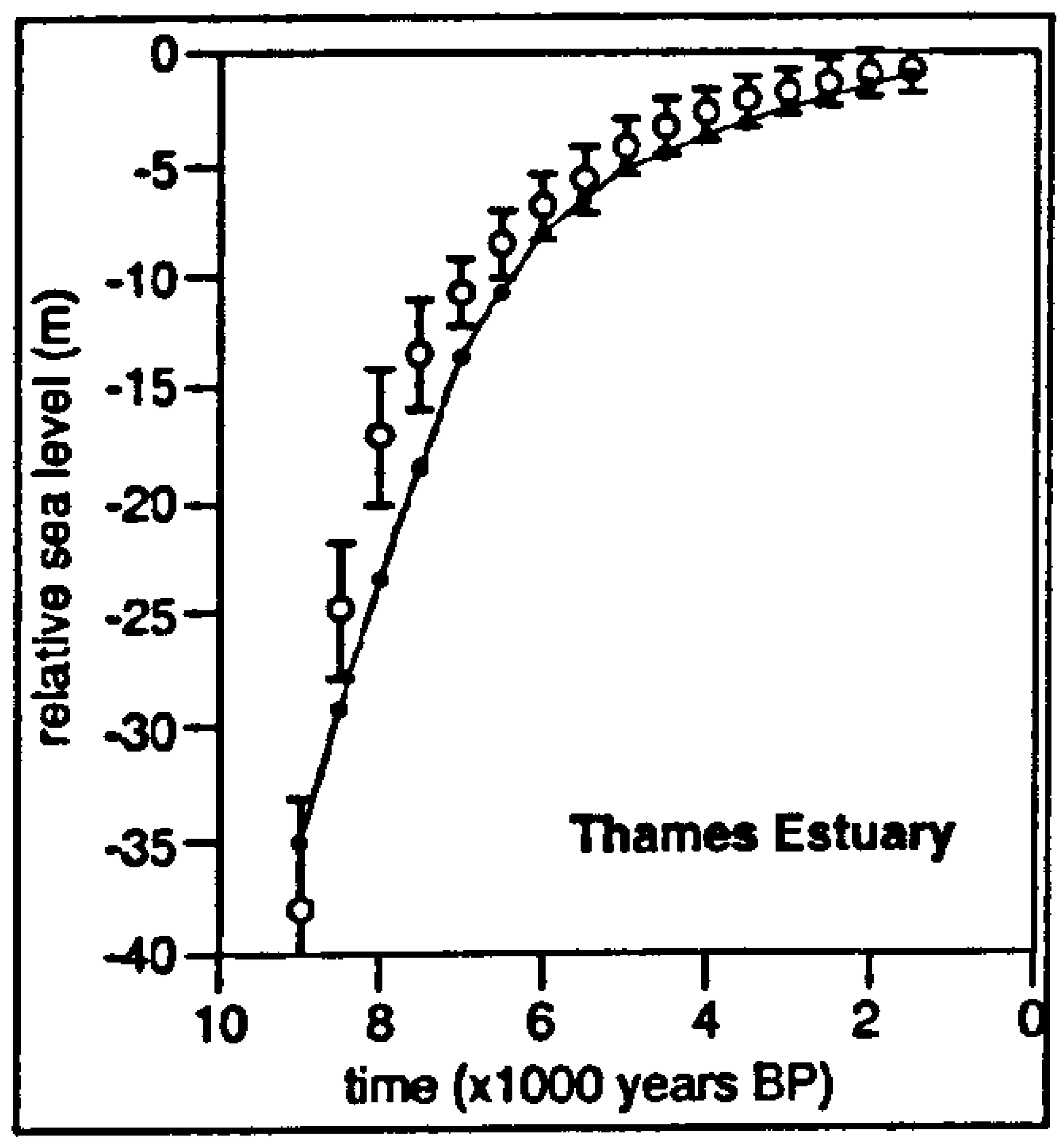

Fig. 2.29 Observed versus predicted data for the Thames Estuary (After Lambeck, 1995).

Fig. 2.28 shows that for North Norfolk there is a fairly poor agreement between the observed and predicted data. This is most likely due to the fact that this area is known to be a barrier-dominated coastline, which has affected the pattern of coastal sedimentation and thus the altitude of intercalated peats and silts. The unique setting of north Norfolk has already been discussed in section 2.2 and is therefore not discussed again here.

The observed versus predicted data for the Thames shows a remarkable similarity (Fig 2.29). For the last 5000 years many of the observed data points, within their error bars, lie on the predicted sea-level curve. The model slightly under predicts the altitude of relative sea-level but nothing like as much as at previous sites discussed. This however, could be due to the fact that the work from the Thames Estuary was used to validate the geophysical model (Lambeck, 1990).

For the British Isles it can be seen that the general agreement between observed and predicted data is excellent, however the model tends to slightly under predict the altitude of relative sea-level.

2.3.3 Northern France

Research which compares observed data with geophysically modelled data at sites in northern France has been undertaken by Lambeck (1997). Four main regions were included in the study; Picardie coast, Normandy, Brittany and the Vendee (Fig. 2.30). The Picardie coastline is discussed in further detail in Chapter Eight, however it can be seen in Fig. 2.30 that the overall agreement between the observed and predicted data is good, although the observed data lies above the modelled data by between 1 and 4m.

The comparison between the observed and predicted data for Normandy and Brittany also revealed a close agreement; however in Normandy the model tended to over predict the relative sea-level by about 1m. For the Vendee, although some of the observed data points plot on the line of the predicted data, there are really too few observational data points to be able to make a reliable comparison.

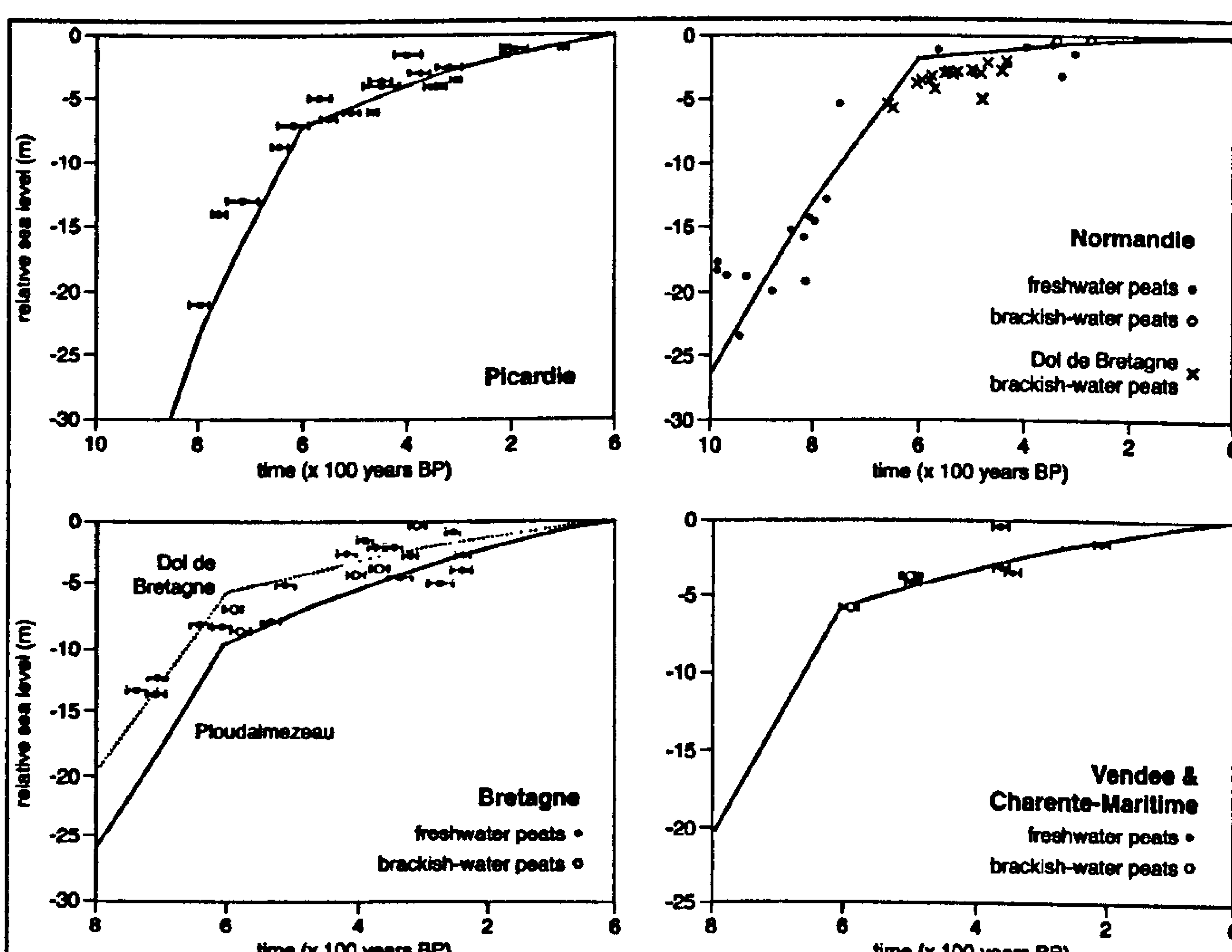

Fig. 2.30 Observed versus predicted rates of relative sea-level change for Northern France. (After Lambeck, 1997).

2.3.4 Conclusion

A discussion of the previous comparisons between observed and predicted data has highlighted a good general agreement between the datasets. However, at all sites, except Normandy, northern France, the model slightly under predicted the relative sea-level change. The possible reasons for this are discussed in Chapter Eight, where the work of Lambeck is compared to the results from the three study sites; the Pevensey Levels, the Canche Estuary and the Somme Estuary and proposals for the validation of the model are discussed.

Chapter Three Methodology

The aim of this chapter is to describe the sites that were examined and to provide an account of the analyses that were undertaken. The first section will describe the three field sites and how they were selected. The second section will then be divided into analysis undertaken in the field and analyses undertaken in the laboratory. A review of the different types of methods available to the study of Holocene sea-level change is provided in Chapter Two and therefore not discussed again in this chapter.

The methodology selected by this research was chosen to reflect the characteristics of the field sites which were being studied. As previously discussed above, the sites were all estuaries that had once been under a marine influence, that were small enough in size to be able to identify the effects that local coastal processes had had upon the pattern of sedimentation. Previous research had indicated that local factors play a significant role in the development of estuarine sediments (Long & Innes, 1993; Shennan, 1986b). However, it is also widely accepted that regional scale changes in sea-level can be detected (Kidson & Heyworth, 1978; Shennan, 1986b). Thus the search for regional scale sea-level signals was carried in out in order to try and determine whether local or regional factors had been responsible for the pattern of sedimentation recorded at the sites either side of the Channel.

The time/altitude approach was favoured over the sea-level tendency approach, because the collection of sea-level index points enabled cross-channel events to be more clearly identified. The tendency approach would simply have allowed similar phases to be compared, rather than actual altitude restricted timings to be compared. The time/altitude approach also enables the indicative range to be determined (Shennan, 1982) which enables a greater accuracy when attempting to establish past tidal levels.

3.1 Site selection

In order for a cross channel study to be performed it was necessary to identify comparable estuaries either side of the English Channel. With the aim of furthering the progress of sea-level studies in both regions it was important to use sites that had not previously been studied as part of a sea-level reconstruction. Tooley (1978) suggested using a small homogeneous area in order to minimise tidal inequalities, earth movements and geoid variations and recommended that samples come from similar palaeo-environments and have the same indicative meaning. The final recommendation was that radiocarbon dates be checked against standards as described in regional pollen diagrams.

At the outset of this research, a set of criteria were outlined to assist in identifying potential sites. Firstly, it was decided that sites would be chosen along coastlines that are emergent, that is, they would be estuaries that had previously been under marine influence but were now fully terrestrial or partially reclaimed wetland or marshland. Secondly, that the criteria outlined by Godwin (1962) would be followed. This meant that it was necessary for the sites to be near a current estuary and for ground altitude to be below 7m OD. Thirdly, it was important to try to find estuaries that allowed inter-site and intra-site comparability. Of particular interest was the presence or absence of a coastal barrier as these exert a significant control upon the formation of intercalated peat and minerogenic layers (Jelgersma, 1961, Jelgersma *et al.* 1970). An open coastline may experience more regular marine inundation than one completely protected by a coastal ridge, which would need to be breached, before a marine incursion could occur. When interpreting the sediment record and thus sea-level record it is vital to know whether an estuary was open or barrier-protected. Estuaries that have been protected from the influence of fluctuating sea-levels will exhibit a greater number of inter-calations resulting from changes in the barrier stability. If an estuary has been protected by a barrier and the barrier is subsequently breached it is essential to know whether this was the result of a rising sea-level or whether it was the result of a breach in the barrier caused by another factor, such as a change in sediment supply. For example Romney Marsh exhibits deposits where "peat developed in the shelter of a shingle bank, which broke periodically to permit deposition of marine silt" (Eddison, 1983 p. 44).

In southeast England many estuarine valleys have had a sea-level history study undertaken on them; Romney Marsh (Eddison, 1983, Long & Innes, 1993), Walland Marsh (Waller *et al.*, 1999), Thames Estuary (Devoy, 1979), Essex (Greensmith & Tucker, 1980) and Eastbourne (Jennings & Smyth, 1990). As part of this study several possible sites were identified and preliminary stratigraphic surveys were undertaken. These included sites at the Pevensey Levels, East Sussex; Oare Marsh, North Kent; Luddenham

Marshes, North Kent; Wingham, North Kent and Wantsum near Margate, North Kent (see Fig. 3.1).

Preliminary stratigraphic survey was undertaken at each of these sites which involved the collection of a series of hand cores. Wingham had previously been worked on by Godwin (1962) and is currently being studied by English Heritage as part of a larger project (Wells & Waller, 1999). The research undertaken was included in an English Heritage report but any further fieldwork was abandoned and has not been included in this PhD. The site at Wantsum, near Margate although potentially a good site due to its position along the coastline and altitude above present sea-level did not reveal consistent buried peat layers. Oare Marsh in North Kent revealed an excellent stratigraphic record although once again buried peat layers were inconsistent. Although detailed work was not carried out on the site it would provide an excellent site for future sea-level research. A sample taken from Luddenham Marshes near Oare Marsh also revealed an excellent stratigraphic record, however, obtaining permission to carry out further work proved difficult and further work was not pursued.

Having carried out extensive preliminary investigations at several sites it was decided that the Pevensey Levels met all the criteria set for this research and having not been comprehensively studied before, it was selected as the site in south east England.

In an attempt to locate comparable sites in France three estuaries were examined, the Canche, Authie and Somme (see Fig.3.1). The same criteria were set, however it must be noted that no sites comparable in size to Pevensey were identified. Of main importance was geographical location. Firstly, it was essential that they were along the Channel coast. Secondly, that both an open and a barrier protected coast were included. Thirdly, that no previous sea-level studies had drawn conclusive results, and finally that the sites were close to the UK in order to allow regular visits to be made. Preliminary stratigraphic investigations at each site revealed that the Authie did not exhibit consistent buried peat layers, which could have been because this site was the most open of the three. It was thus decided to pursue only the Canche and the Somme as it was believed they would be more sensitive to the sea-level signal.

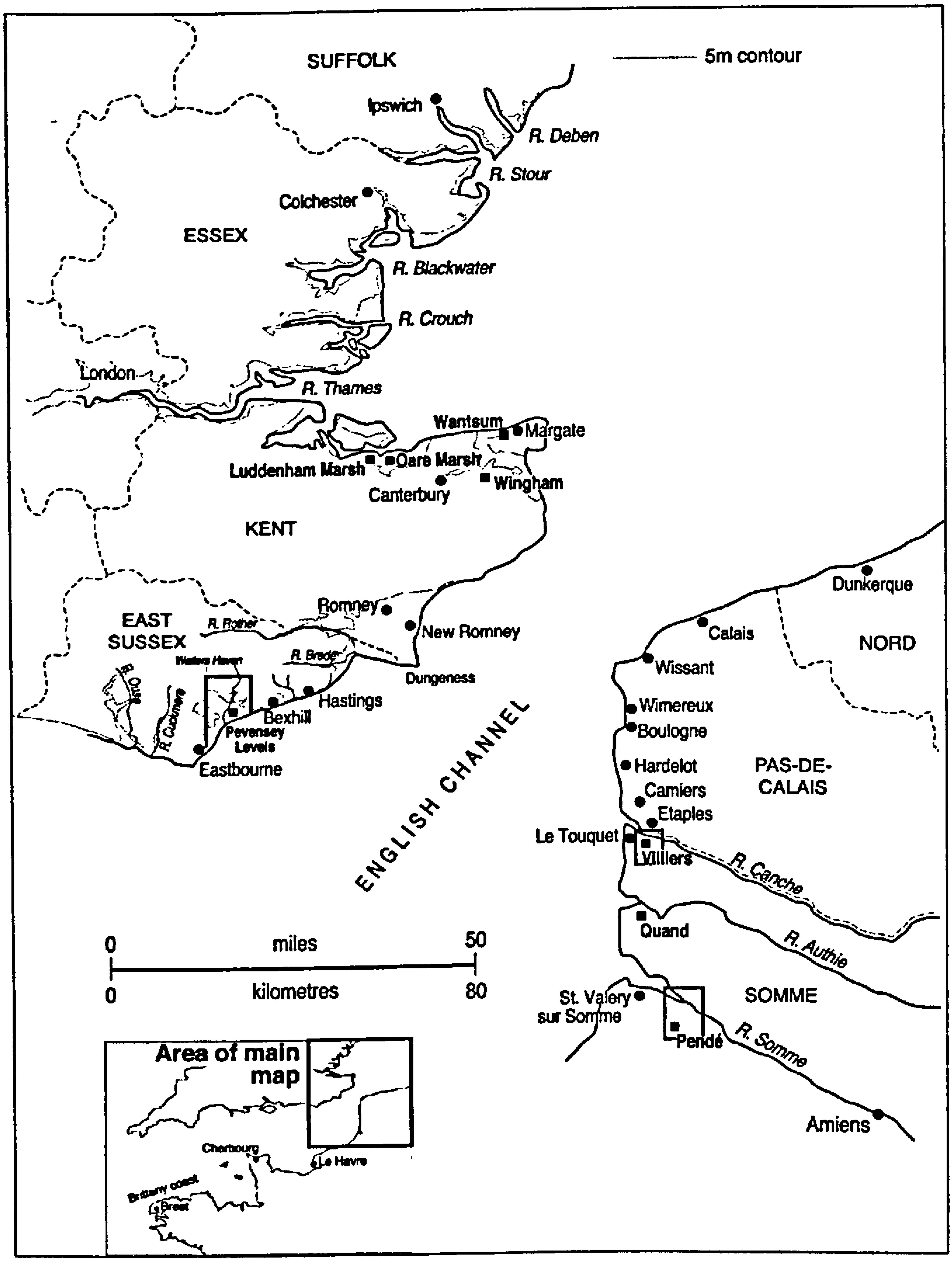

Fig. 3.1 Map of field sites in south east England and northern France
(the boxes denote the study sites)

3.1.1 Pevensey Levels, East Sussex, South East England

The Pevensey Levels are situated between Eastbourne and Bexhill on the south coast of England (see Fig.3.1). Most of the area is a designated Site of Special Scientific Interest (SSSI) managed mutually by Sussex Wildlife Trust, the Environment Agency and English Nature. The area lies in the chalk dominated region of the south coast and in geological terms is young, having formed in the last 10,000 years. Prior to this period the sea would have covered most of the estuary. Historical documents dating back to the Roman times refer to Pevensey as a port, possibly a shallow bay (Dulley, 1966) and a shingle barrier is thought to have run the length of the levels enclosing behind it a substantial area of marshland. By the Medieval period the primary industry was saltworks (Dulley, 1966). By the end of the Middle Ages this was declining, possibly due to the falling salinity levels on the marsh brought about by a significant sea-level fall. After this sea-level is believed to have risen again and management of the coastline has occurred since the Middle Ages. This has included the construction of seawalls and intensive reclamation of the land. By the late 1200s the sea was rising once more (Dulley, 1966), with severe floods being documented and by the mid-1300s there are reports of prosperous farming communities living on the levels, which can only suggest sea-level had fallen once more.

The Levels are currently pastureland, consisting of managed (drained) land, connected by an intricate system of dykes and ditches. It is now part of a Wetland Enhancement Scheme managed by the Environment Agency that involves the "wetting-up" of soils via ditch level management. The coastline is currently managed by the Environment Agency and in 1998 a major sea defence scheme began using the shingle beach as a natural defence to protect 50km^2 area and man-made structures. Shingle was imported into the area to widen and extend the beach by 25 metres and 126 timber groynes were replaced. 23 rock T-head structures were also put in place on the sandy foreshore. However, the area is still regularly breached, most recently in the winter of 1999.

The present Mean High Water Spring Tide (MHWST) at Pevensey is +6.3m OD and Mean Low Water Spring Tide (MLWST) is –3.2m OD (Environment Agency data). Mean sea level for Pevensey or Eastbourne nearby is not available as no tidal data were available. However, the Hydrographic Office has inferred values for Eastbourne based on the Standard Port of Shoreham. Highest Astronomical Tide (HAT) is given as 8.1m and LAT as 0.1m above chart datum (Hydrographic Office *pers. comm.*).

3.1.2 Canche Estuary, Pas de Calais, NW France

The Canche is a small valley north of the Somme and Authie estuaries (see Fig. 3.1) situated near Le Touquet-Paris-Plage. There is currently no barrier protecting the coastline, however it is believed that one used to be present (Buen & Broquet, 1980). The Canche has not previously had a sea-level reconstruction undertaken on it. It is a chalk-dominated coastline and presently no shingle barriers are in place. It is bound to the north by an extensive dune system named the "Dunes Picardes". At the mouth of the estuary, near the port of Etaples, the sides of channel are currently occupied by a saltmarsh system. Few studies have been undertaken on the estuary, both on the river and the Quaternary sediments. Previous research has focused on the dune development and the stability of the nearby chalk cliffs and thus the scope for further work is there. The land is currently pasture or agricultural land, and a large area north of Etaples is a nature reserve.

Current mean sea level for the Canche is 5.07m. Present MHWST is 7.18m, HAT is 10.4m and MHW is 6.22 (data are based on calculations provided by SHOM, 2002). The importance of this information will be discussed in the Results chapters.

3.1.3 Somme Estuary, Picardie Coast, NW France

The Somme Estuary is situated on the Picardie coast between Quend and Ault (Fig. 3.1). The basin of the Somme is 5800km^2 (Antoine, 1998) and its geology is chalk dominated. The Picardie coastal plain is 60 km long and consists of a series of Holocene shingle bars (Sommé, 1998). The plain extends from the River Authie in the north to the River Bresle in the south. Beneath the Holocene sand and shingle deposits, Pleistocene fluvial and marine deposits have been found at depths of –8.9m to –18.35m NGF (Sommé, 1998). The river terraces have been most extensively studied by Antoine (1998), details of which are given in Chapter 2. The Somme is a barrier-protected coastline, currently shown by the presence of a shingle spit, maintained by material from the south, which currently extends from Ault in the south to Le Hourdel in the north. A seawall and a number of drainage ditches are also in place to manage the water level across the estuary.

The area exhibits an extensive salt marsh that is dominated by middle marsh vegetation and an intricate channel system is present either side of the river valley. Brackish and fresh water supplies allow for a high range of plants and invertebrates to exist. The vegetation on the marsh is dominated by *Limonium vulgare* (sea lavender) and by *Salix* at the edges.

Similar to Pevensey having SSSI status, the Somme is a Zone d'importance communiutaire pour les Oiseaux (ZICO) which means it is a Special Protection Zone (ZPS) and under European designation is a Special Area of Conservation (SAC).

Current mean sea level at the Somme is 4.84m. MHWST is 6.92, HAT is 9.65m and MHW is 6.0m (data supplied by SHOM, 2002 *pers. comm.*).

3.2 Field methodology

This section will provide information about all analysis undertaken in the field. This includes the stratigraphic investigations and description of sediments and the subsequent levelling of subsurface units.

At each site being examined, stratigraphic survey was undertaken using a hand held screw auger to remove the upper 0.5m of sediment and then soil gouge auger to sample the remaining sediment units. A systematic sampling system was employed, with boreholes being sunk at 250m intervals along a straight line transect, where possible. This sampling system was adopted in order to assess the importance of the relationship between distance from the coastline and the altitude of the peat layers, thus determining the pattern of peat deposition across the estuary. Following a marine regression, peat will usually form earlier up-valley and will therefore be found further below the surface. A marine transgression will therefore have the opposite effect producing deeper peat layers towards the coast. Transect directions and the number of boreholes sunk varied depending upon the size of the site. Maximum depth was attained, ceasing when it was not possible to penetrate the sediment further, usually the presence of a sand, gravel layer or bedrock. Typical core depths at the sites varied between 5 and 8 m below the surface.

Biostratigraphic data was obtained from each unit of sediment, from each of the sample cores, from each study site. An emphasis was placed on the collection of biostratigraphic samples from across the stratigraphic transitions. Using a 10-centimetre range, five centimetres above and five centimetres below the stratigraphic contact, samples were obtained every centimetre. This resulted in a greater number of pollen, diatom and foraminiferal samples being taken from the stratigraphic boundaries than from throughout the sediment units. A larger sampling range was used throughout the sediments, with samples being collected every 10 centimetres, or more from some of the more extensive units.

Despite the sampling emphasis being placed across the stratigraphic boundaries, the biostratigraphic data from each of the samples cores is constrained according to the stratigraphic unit, and not by local assemblage zone or by placing the emphasis on the transitions. It was decided that presentation of the results by stratigraphic unit allowed the results from the different study sites to more directly comparable, thus simplifying the cross-channel comparison.

3.2.1 Pevensey Levels, East Sussex, SE England

At Pevensey, 31 boreholes were sunk as part of the stratigraphic survey. These were taken in a 6.5 km transect perpendicular to the coast in a south-north direction, every 250 metres from Normans Bay (Grid reference TQ672 059) to Gildridge Farm (TQ620 108). Fig. 3.2 shows the location of the transect of boreholes. The descriptions of the boreholes may be found in Chapter 4 and in greater detail in Appendix II. As at all the sites the upper disturbed stratum was removed using a screw auger and subsequent samples using a 50mm length, 30mm diameter gouge auger. All sedimentological descriptions were classified according to the Troels-Smith classification (1955) and recorded in detail.

Borehole 2 (refer to Fig. 3.2) near Wallers Haven (Grid reference: TQ661 065, Lat. N 50° 10' Long. E 21° 40') at Pevensey was found to be most representative of the stratigraphy and provided the greatest potential number of sea-level index points as shown by changes from organic to inorganic sediments. A sediment core sample was collected using a Livingstone type piston corer with a Pjonjar hammer attached. The piston corer allows a larger sample to be collected which is advantageous when carrying out several different analyses on the same core. It also permits an uncontaminated and relatively undisturbed core to be extruded. The sample core was then tightly sealed in plastic wrap and returned to the laboratory for analysis. As advised the samples were stored in a cool and dark environment. This prevents the core from drying out and shrinking. In this case a cold dark room was used.

At this stage it is necessary to mention that at the request of one of the landowners at Pevensey, the locations of four boreholes have to remain anonymous. The positions of these boreholes are therefore not represented on any figures throughout this research, however the stratigraphic record is presented in Chapter 4.

All boreholes were levelled relative to ordnance datum (OD) using an Electronic Distance Metre (EDM) or manual level to two benchmarks one at Church Acre Bridge (TQ 6476 0748 Church Acre Br. N side road, altitude 2.74m OD) and the second at New Bridge (TQ 6265 0967 NBM Wall Pumping Station NW side NW face. Altitude 2.57m OD).

3.2.2 Canche Estuary, Pas de Calais, northwest France

At the Canche a transect of boreholes was taken parallel to the coastline from le Tertre to Champ Laby near Villiers (Fig. 3.3). 12 boreholes were extracted using the same method as described above. A systematic stratified sampling system proved more difficult than at Pevensey. Obtaining permissions was more complicated and thus in some places gaps in the transect are present. Borehole BH4 (Lat. N 50° 29' Long E 1° 40') was found to be the most representative and provided the greatest number of potential sea-level index points. This was subsequently sampled using the Livingstone piston corer and sealed and returned to the laboratory for further analysis.

Few studies have been carried out which have attempted to measure the difference between datums, Pirazzoli (1996) stated that mean sea-level at Marseilles is 11cm above that at Newlyn. However, a more recent figure was calculated during the construction of the Channel Tunnel. It was found that OD is 0.3788 metres higher than NGF, calculated in 1994 by Ordnance surveyors (Davies *pers. comm)*.

The height of each borehole was determined by levelling to the IGN benchmark situated on the exterior wall of M. Guy's property, 0.58m above the ground at le Moulinel (reference number B'.F.03 – 19) at an altitude of 10.724m above Niveau General Francais (NGF).

3.2.3 Somme Estuary, Picardie Coast, NW France

Ten hand held boreholes were sunk and recorded along a transect perpendicular to the coast in a small, contained inland valley between Pendé and Estrebœuf along the l'Amboise river, a tributary of the Somme (refer to Fig. 3.4). The site was much smaller than the Pevensey site and, thus, fewer boreholes were required in order to obtain a representative stratigraphy. The presence of many ponds or "etangs" made taking systematic sampling difficult. In some instances it was also not possible to obtain permission from the landowners and thus a gap is present in the transect. Borehole BH9 (Lat. N 50° 10' Long. 1° 37') provided the most interesting and representative stratigraphy and was thus selected to be the sample core. This core was then extracted using the Livingstone piston corer. The sediment was tightly wrapped in plastic film and stored in a cold dark room until laboratory analysis was undertaken.

The height of each borehole above sea-level was determined by levelling to a benchmark situated on the church in Estrebœuf located 0.76m above ground in the nave of the church buttress (reference number N.C.03 – 28) which has an altitude of 9.237m above NGF.

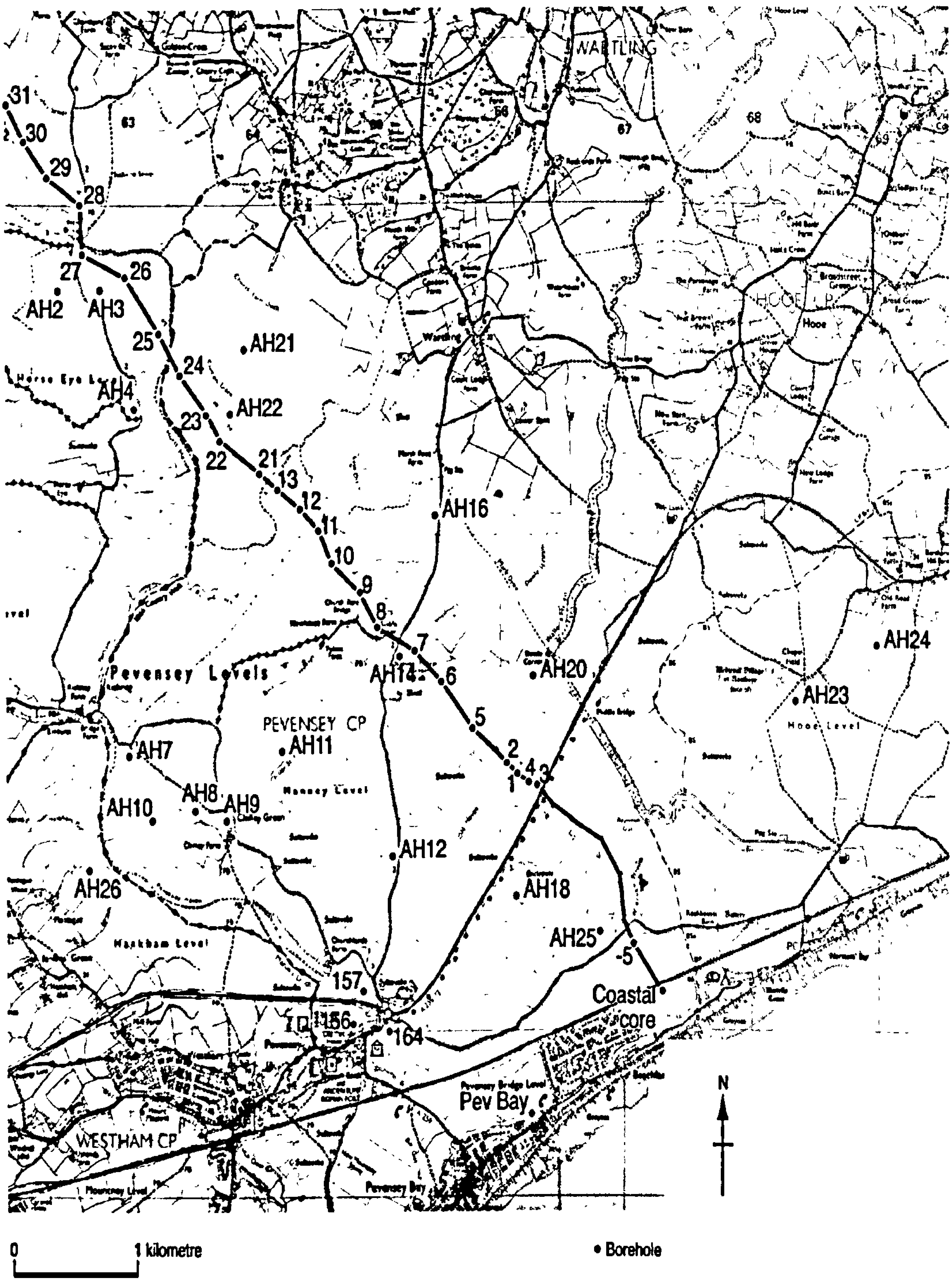

Fig. 3.2 Transect of boreholes collected from the Pevensey Levels, East Sussex

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3.2.4 Authie Estuary, Picardie Coast, NW France

In addition to the Canche and Somme, a third estuary had originally been identified as a potential site. Anthony (2000) described the Authie has being "a rapidly infilling macrotidal estuary" (p.109). It provided a "good example of an estuary whose advanced sandy infill has been due to direct supply from the sea, from updrift erosion of the coastal dune barrier and from recycling of the dunes lining its northern shore" (Anthony, 2000 p.109). A sea defence programme that includes a breakwater, dune front armouring and groynes, currently protects the coast at Berck. The problem of coastal flooding is a current issue, the last storm surge occurring in 1990. Anthony (2000) concluded that the fate of the estuary is "complete silting up, ending up as a narrow, weakly tidal channel" (p.120).

Preliminary investigations were carried out, with three hand held cores being collected, recorded and levelled as above. Two cores were taken on land lower than 4m and a third on a marsh at Tigny. All cores were levelled to temporary bench marks (bridge). However, as buried peat layers were inconsistent it was decided that no further research would be undertaken. Anthony (2000) also stated that "Nothing is known of this sedimentary infill for lack of boreholes" (p.110) highlighting the potential for further research.

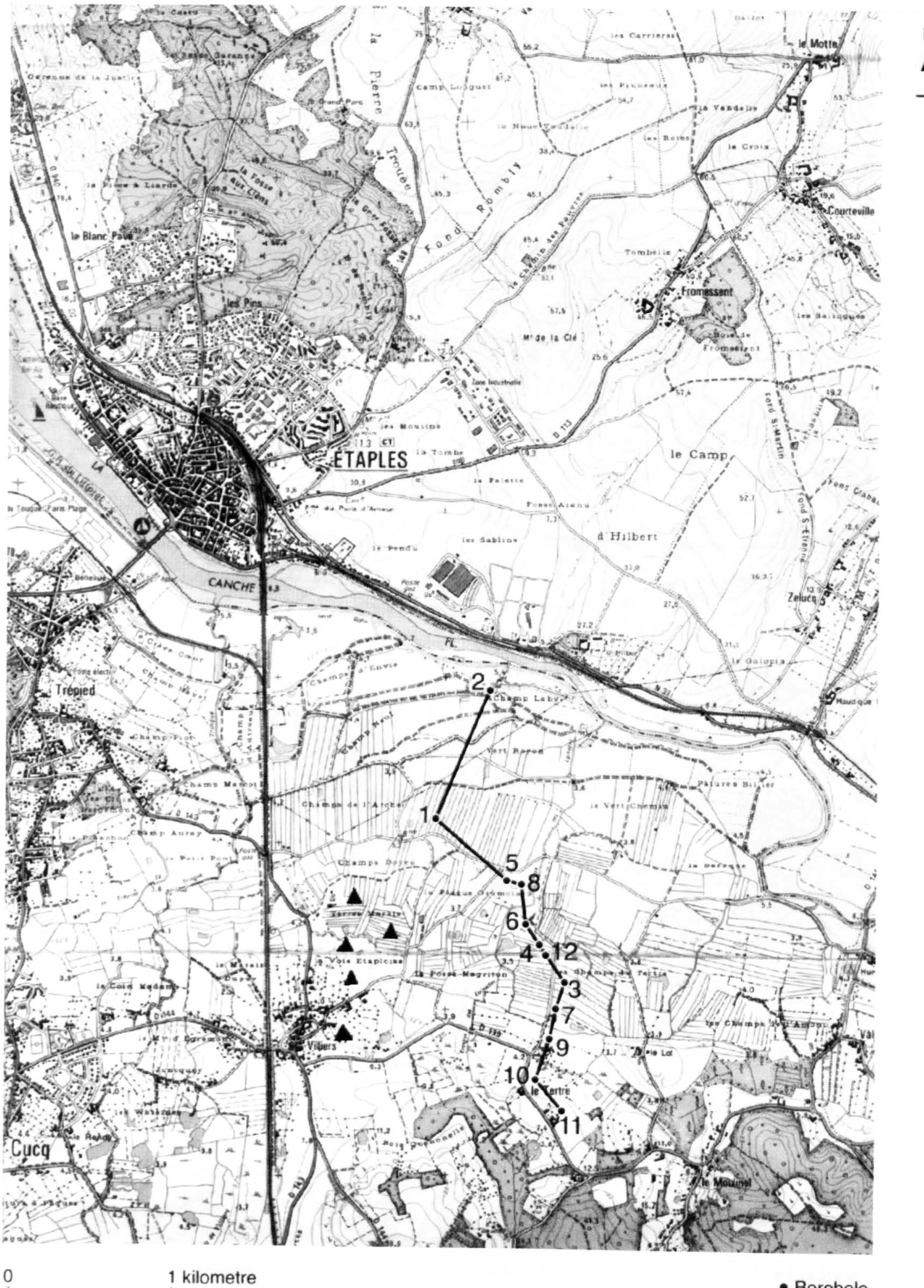


Fig. 3.3 Field map of the Canche Estuary, NW France showing the position of the boreholes. ▲ refer to BGRM borehole positions

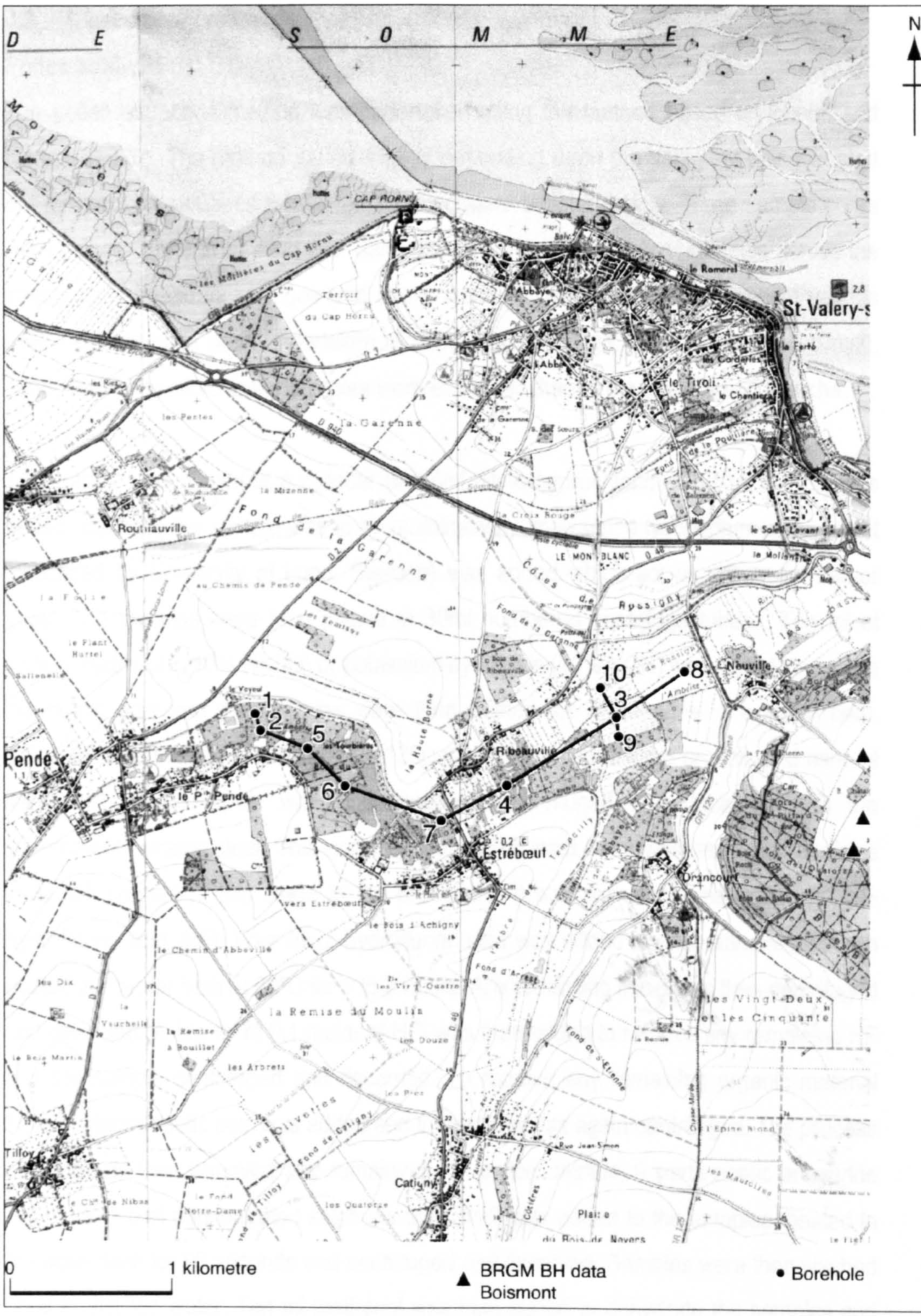


Fig. 3.4 Field map of the Somme Estuary, NW France showing the position of the boreholes

3.3 Laboratory methods

Pollen analysis

The pollen extraction method was undertaken using the method based on Faegri and Iversen (1975). The method varied slightly depending upon the sediment being treated but for most preparations it followed the procedure outlined below. Three sample cores were selected, one from each site. Samples were then taken at 1cm intervals across the stratigraphic boundary changes and every 2-3cm throughout the peat layers. Previous pollen studies have been undertaken at Pevensey (Jennings, 1985; Jennings & Smyth, 1985, 1987), therefore fewer samples were examined than at the Somme and Canche.

The sample was placed in a cylinder and 4ml dilute hydrochloric acid (0.1 M HCl) was added. Because the sample was to be quantitatively analysed, a lycopodium spore tablet (produced by University of Lund, Sweden) was added which act as an exotic marker grain. The samples were then placed in 30ml numbered centrifuge tubes. Ten ml of sodium hydroxide (10% $NaOH$) or potassium hydroxide (10% KOH) was added to remove the humic acid and the samples were then heated for 20 minutes in a water bath. Samples were then passed through a 125µm sieve to remove large organic and mineral fragments. The samples were then washed, centrifuged and decanted until the supernatant became clear. This normally required at least three washes. If clay particles were still present at this stage in the procedure, it was sometimes necessary to use hydrofluoric acid (HF). Four ml of hydrofluoric acid was added to each sample and then heated in a water bath at 99°C for 1 to 2 hours. Any remaining liquid was then centrifuged and decanted. A few ml of 0.1 molar of HCl was then added to remove any remaining HF and the sample centrifuged and decanted. To remove any remaining organic material 10ml of glacial acetic acid was added and the sample was again centrifuged. The process of acetolysis then removed any remaining non-pollen detritus. 9 parts acetic anhydride (54 ml) to 1 part concentrated sulphuric acid (6ml) was added to the samples, heated in the water bath for 90 seconds and centrifuged and decanted. Samples were then washed once in distilled water. Ten ml methanol was then added to dehydrate the samples and preserve them, and the sample centrifuged and decanted (twice). The final stage was to add 4 ml of toluene, then centrifuge and decant the sample. Samples were then transferred using toluene in to vials, excess toluene removed by pipette and silicone oil added to preserve the pollen.

Each sample was then quantitatively analysed by counting a minimum of 300 pollen grains when possible. The concentration was determined using lycopodium spore tablets as marker grains. Lycopodium is used because it is not commonly found in European samples. A single spore tablet of Lycopodium contains 13,911, with a standard deviation of 689 and a coefficient of variance of 4.95% (Lund University *pers comm*).

Throughout this study the classification and identification of pollen taxa has been based upon the work by Moore *et al.* (1991) and Faegri & Iversen (1989).

Diatom analysis

The method of diatom extraction throughout the research followed Battarbee (1986). Samples were taken at a 1cm resolution across each stratigraphic boundary and every 10cm throughout sediment units. The technique applied in preparing the samples was dependent upon the type of sediment. In sediments containing salts soluble in hydrochloric acid, carbonate and metal salts and oxides may be removed using dilute HCl (10%). Most samples in this study however, were prepared using the following procedure.

Organic matter was removed by the process of oxidation, which involved hydrogen peroxide (30% H_2O_2) being added to a 0.1g of dry sediment and the samples heated in a water bath for 2-4 hours. Two ml of HCl (37%) were then added to remove calcium carbonates. Samples were then washed in distilled water, centrifuged and decanted four times. Dilute ammonia solution (1% NH_3) was added for the final wash to remove any particles of clay which might remain. DVB glass microspheres (produced at University College London, 1998) were added to permit the samples to be quantitatively analysed. The diatom solution was then diluted until neither clear nor milky in appearance and 0.5 ml of solution pipetted onto a coverslip and mounted on a slide using Naphrax (NBS Biological Supplies). Lastly the slide was heated gently on a hotplate to allow the toluene present in the Naphrax to be driven off and slides were left overnight to set.

This study used DVB microspheres to quantify diatom concentrations. 2ml of microsphere solution was added in concentrations of $5x10^6$ per ml. In this study the use of microspheres was employed because they offered a cheap and easy method and they are most widely used in Quaternary studies.

The classification of diatoms was achieved using Hartley (1986) to identify the coastal diatoms, Hendey (1964) to identify all diatoms and Barber and Haworth (1981) to identify freshwater species.

Diatom-based transfer function

The diatom data that were collected from each site were put through the diatom-based transfer function devised by Zong (private communication), to whom I am indebted, in order to establish the palaeo-tidal level of the samples. A full discussion of the transfer-function based on the work on Zong & Horton (1998; 1999) can be found in Chapter Two. The calibrated output data file is presented in Appendix III. Tolerance down-weighted weighted averaging was found to perform better than ordinary weighted averaging, providing a lower root mean square error (RMSE). Each sample was assigned a standardised water level index, which was then back-transformed to metres depth OD or NGF (refer to equation 4.3.1.1 in Chapter Four). Each sample was then given a value to a reference water level, in this case mean high water spring tide. The implications of using the training set from sites other than those being investigated is discussed in the results chapters (Four, Five and Six).

Foraminiferal analysis

Foraminiferal analysis was undertaken on the inorganic sediments across stratigraphic boundaries. The foraminiferal extraction method employed in this study is based upon 5 cm^3 sediment sample was dried in an oven for 1 hour at 110°C or air-dried overnight. The sample was then weighed to obtain the dry bulk weight. Disaggregation of the sample was undertaken by soaking the sediment in sodium hexametaphosphate (calgon) overnight. The sample was then wet sieved using 500 and 63μm sieves and the greater than 63μm fraction was retained and air dried. The sample was then coned, quartered and examined. If species were abundant, 250-300 specimens were dry picked under a reflected light microscope (Haslett, 1998). Low counts, i.e. less than 30 foraminifera per sample, are excluded from the data set (Gehrels *et al.*, 2001).

If microfossil density was low (commonly in the sandy deposits) it became necessary to concentrate the sample using a flotation method. Sodium polytungstate is a heavy liquid, which has a density of 2 grams per cm^3. This allows the sand to sink and the foraminifera to float, which can be decanted off onto filter paper. The technique of using and recycling sodium polytungstate is still in its infancy and finding a successful method was challenging. This method proved expensive and difficult to perfect and was therefore not pursued.

3.4 AMS radiocarbon dating

In order for sea-level curves to be produced, sea-level index points need to be determined. These are points for which altitude; age and sea-level tendency are known. In this study it was decided that accelerated mass spectrometry (AMS) radiocarbon dates would be used rather than conventional radiocarbon dates. Due to the fact that several analyses were being undertaken on the samples cores it meant little sediment remained. AMS dates require a smaller sediment sample than conventional dates.

Once collected, the samples were stored in the freezer in double bags to prevent any contamination. The samples were prepared at the NERC radiocarbon laboratory in East Kilbride, Scotland using the following procedure:

1) Carbon oxidation preparation:
   - C (Sample) + $O_2 \Rightarrow CO_2$ — Oxidation
   - C (carbonate) + $H^+ \Rightarrow CO_2$ — Hydrolysis
2) Lithium carbide formation:
   - $2CO_2 + 10Li \Rightarrow Li_2C_2 + 4Li_2$ — Heated at 510°C
3) Acetylene production:
   - $Li_2C_2 + 2H_2O \Rightarrow C_2H_2 + 2LiOH$
4) Benzene synthesis:
   - $3CH_2H_2 \Rightarrow C_6H_6$ — Chromium catalyst (200°C)

In total, 30 AMS radiocarbon dates were obtained and used to produce sea-level index points. All the samples were prepared to graphite stage at the NERC Radiocarbon Laboratory, East Kilbride. Samples were digested in 2M HCl at 80°C for 8 hours, washed to remove any mineral acid and digested in 0.5M KOH at 80°C for 2 hours. The process of digestion was repeated until all humic acids had been removed. The remaining residue was rinsed to remove alkali and was then digested in 1M HCl (80°C for 2 hours). Finally the samples were rinsed free of acid, dried and homogenised. Once in graphite form, samples were sent to the Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory, University of California and the University of Arizona NSF-AMS facility for ^{14}C analysis. All the radiocarbon dates were calibrated using Calib 4.3 (Stuiver & Reimer, 2000) and are cited using 2 σ.

3.5 Compaction and consolidation of the sediments

It is widely known that unconsolidated sediments, such as those present within coastal estuaries, will autocompact. Allen (1999) defined this as the process by which a growing sequence of sediments collapses due to self-weight. It is important to establish the amount of compaction that has taken place in order to eliminate the errors involved in the collection of observational data. Compaction will affect sedimentation rates, increase the amount of apparent land subsidence, alter the altitude of sea-level index points and create problems when attempting comparisons between sites or predicted data. Each sediment type will respond differently but all will experience an exponential rate of compaction with time, ultimately reaching a point where no further consolidation is possible. Therefore, theoretically it should be possible to calculate the rate of sediment compaction for each sediment type.

There are a number of methods currently available to decompact sediments, as described by Allen (1999). Kaye & Barghoon (1964) used the compressibility of wood to measure peat compaction in Massachusetts, USA. The rate of compression was calculated using the log equation *C= T'/T* where T' is the present thickness and T is the original thickness. The most common approach however, is the geometrical method, whereby peat compaction is calculated from the changing altitude of those peat bed surfaces which are assumed to be isochronous (Bloom, 1964; Belknap & Kraft, 1977; Allen, 1996 and Haslett *et al.*, 1998). Bloom (1964) used sedge peat samples to determine how a single peat bed will compact under the weight of estuarine mud. The study concluded that the sedge peat had compacted to between 13 and 44 % of its original thickness over 7000 years using the equation *C=ratio of present thickness / original thickness*. However, this can only be employed when the amount of displacement and present thickness are known.

Paul & Barras (1998) developed a one-dimensional numerical model to calculate the self-weight compression of clay from the Forth Valley, Scotland, using liquid limit values, in order to correct sea-level index points. The study found that compressible sediments required a 5-10% correction, whilst incompressible sediments required a 1-2% correction, thus highlighting that compressibility is more of a problem for sites with thicker deposits of finer grained sediments. This meant that the effects of compaction were much greater on the late Holocene deposits than the early Holocene or Late Devensian. Compression of the sediments was found to affect the sedimentation rate, with a greater impact on deeper sediments than on mid-depth sediments. At the study sites in the Forth Valley these findings meant that a 2–5m correction needed to be applied to the sea-level index points in order to allow for compaction of the sediment. Although this research provided a useful starting point, Allen's (1999) method incorporated the findings of this study and furthered the research. Therefore, the method proposed by Paul & Barras (1998) has not been directly employed in this research.

The method employed by Haslett *et al.* (1998) required a basal peat resting on a non-deformable substrate, radiocarbon dating of the peat surface and biostratigraphic analysis of the contacts to assure that the shifts in environments were gradual and not erosive. Assuming that the substrate had not been altered and was incompressible, the amount of compaction of the basal peat was quantified using radiocarbon analysis. Sediment thickness and age were compared between cores and the compaction was calculated to be a maximum of 2.22m with a clay overburden of 3.16m. Haslett *et al.* (1998) concluded that the study of basal peats is one of the only methods of overcoming the problems associated with sediment compaction (p.204). It was not possible to employ this method since no basal peats were recovered from the three study sites.

Following the work of Haslett *et al* (1998), Allen (1999) proposed a method for calculating autocompaction of intercalated sediments based on the work of Skempton (1970). The formula presented was the asymptotic, exponential formula:

$$T = (To - T\min)e^{-KH} + T\min$$

Equation 3.1 Formula to calculate autocompaction (Allen, 1999)

Where T is the final thickness of the sediment, To is the thickness at the time of deposition, $Tmin$ is the limiting thickness (zero porosity), k is the empirical compressibility of the layer and H is the thickness of the sediment overburden.

Values for *K* and *H* were determined from observational data; K=0.537 m^{-1} for peat and K=0.0361m^{-1} for silt and H=1.70 t m^{-3} for peat and 2.60 t m^{-3} for silt (Haslett *et al.*, 1998).

In this research autocompaction of the sediments for each sample core has been calculated using Allen's (1999, 2000) model. Since no basal peats were recovered from any of the study sites, the method proposed by Haslett *et al.* (1998) could not be employed. For each sediment type the bulk density was calculated to ensure that the sediments from the study sites were comparable to those used by Allen (1999). There are however, several shortcomings associated with the model proposed by Allen. Firstly, no accurate time parameter is included. Although the isochrones are based on regular sediment accumulation, thus implying a temporal element no radiocarbon timescales have been incorporated. Secondly, the model assumes the rate of sedimentation does not change over time, an assumption known to be invalid. Thirdly, the model does not allow for a mixture of sediment types to be present in a single stratigraphic unit. Although the silt term allows for up to 20% sand and 20% clay (Allen, 2002 *pers. comm.*).
Allen himself stated, "... the model is exploratory and generic rather than site specific..." (2000 p.239) and despite the shortcomings discussed, the model still provides an acceptable estimate of sediment compaction.

The details of the calculations performed for each of the sample cores at each site are provided in the respective results chapters; Chapter Four, Chapter Five, Chapter Six and Appendix IV.

3.6 Tidal range

It is necessary at this stage to briefly discuss the issues surrounding tidal range. Much of the previous work undertaken on sea-level research has assumed that tidal range has not changed over time. Sea-level index points have been determined using current tidal data as one of the parameters. However, as the research has progressed it has become clear that changes in local factors, such as tidal range, play an important role in determining the pattern of sea-level change. There is a strong relationship between tidal range and the type of coastal features that are present, especially on macro-tidal coastlines, where the tidal range is greater than 4m (Davis, 1964). Tidal range controls the level of high tide and determines the horizontal and vertical extent of the inter-tidal zone (Haslett, 2000). The assumption that tidal range has not varied over time is invalid, although the degree of change is unknown. Unfortunately, there are few methods available to determine the palaeotidal changes during the Holocene (Austin, 1991; Gehrels, 1995; Hinton, 1992, 1995 & 1996).

Gehrels (1995) used a 3-dimensional tide model (3DENS) to calculate the change in tidal range in relation to relative sea-level rise over the last 5000 years. The research in the Gulf of Maine, USA found that MHW had risen by 5-8m over the mid- to late-Holocene, of which 0.42 - 0.52m was due to an increase in tidal range, and the largest contributor was found to be isostatic subsidence. Since the local coastal factors that were recorded in the USA were seen to vary considerably, strongly controlling the results of the model predictions, it was decided not to pursue this method.

Hinton (1992, 1995 & 1996) used palaeogeographic data to determine the influence of water depth and coastline shape on tides in The Wash, UK (Hinton, 1995), revealing that tidal heights have increased with sea-level rise over the last 5000 years. However, this area of the UK appears to be controlled by specific local factors and attempting to model palaeo-tidal changes using the work of Hinton (1995) was not applicable to this research.

Shennan *et al.* (2000) used 26 tidal harmonics to reconstruct tidal regimes in eastern England. Data required included MHWST, maximum tidal level based on astronomical conditions for a 15-day period starting 1st January 1997 and maximum "EC30 model" predictions based on astronomical conditions for the same 15-day period. The results for the area of Dogger Bank; North Norfolk and Well Bank, southern North Sea, covered by the model revealed that tidal range had increased during the late-Holocene. However, in the Fenland from 6000 BP onward there had been a reduction in the height of high tide. Once again highlighting that such reconstructions are highly controlled by local coastal forces and should be performed at the local-scale. The sea-level index points were then re-calculated using the modelled tidal data, resulting in an increase in altitude, causing the new points to lie above those based on current tidal range data. On average, the changes in tidal range for the entire study area resulted in an increase in altitude of 0.64 ± 0.21m. The re-calculated index points were then compared with predicted data (Lambeck, 1995), resulting in an increase in the difference between observations and predictions of relative sea-level, leading Shennan *et al* (2000) to conclude that improved model parameters were required.

Chapter Four Pevensey Levels Results

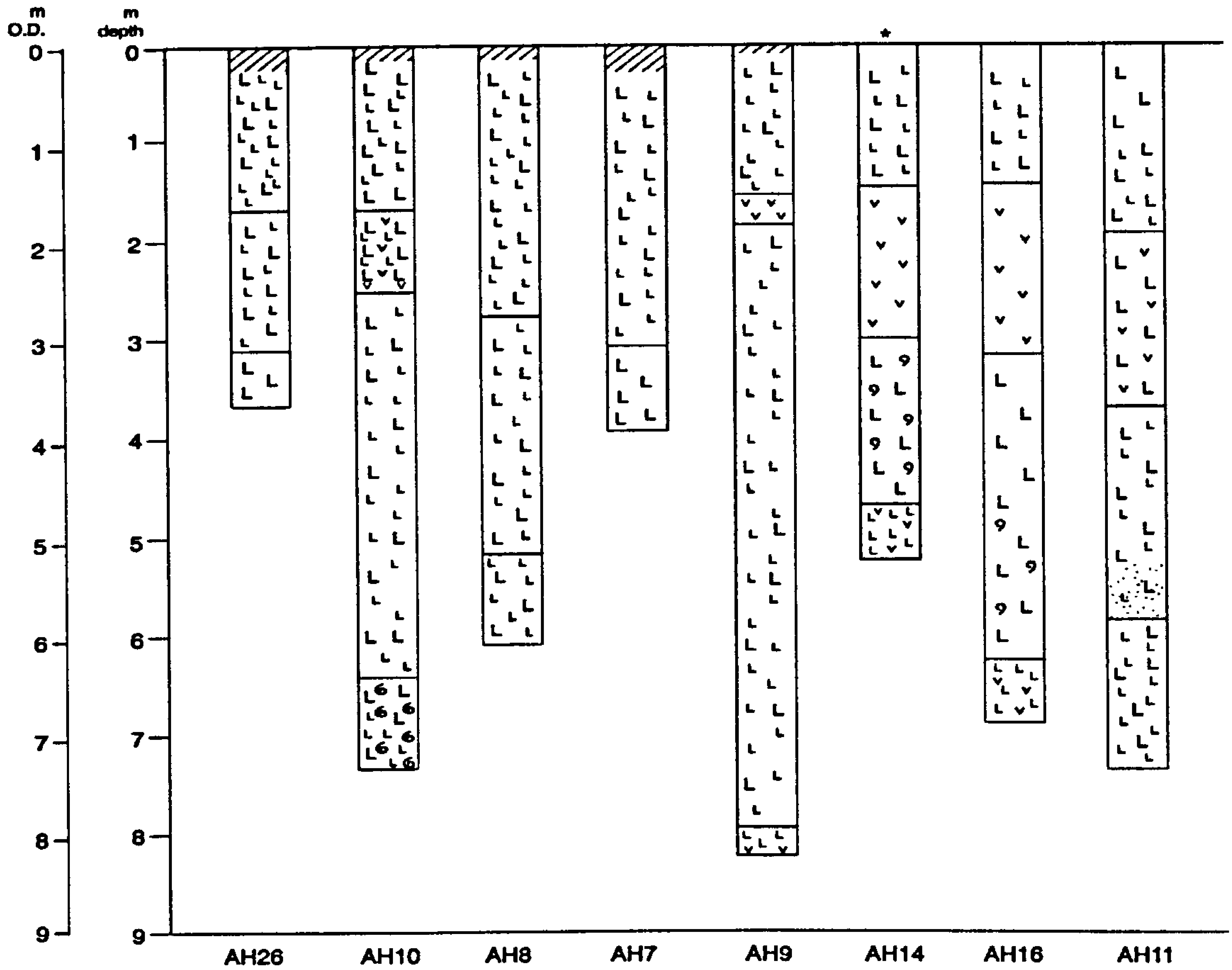
This chapter presents the data collected from the Pevensey Levels, including stratigraphic, pollen, diatom and foraminiferal results. The sea-level history of the site is then presented, based upon the multi-proxy results, and is compared with other sites along the south coast of England.

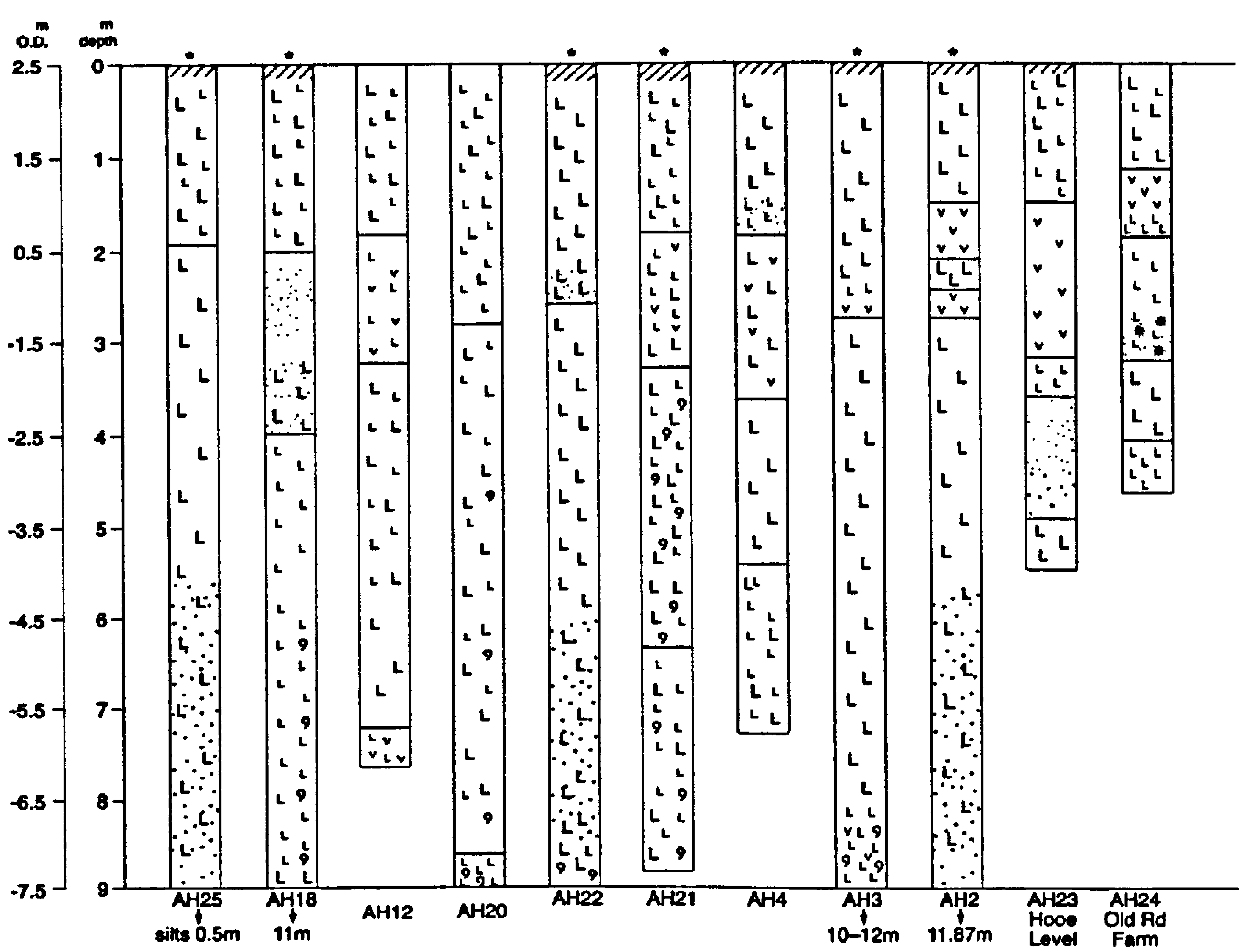
4.1 Stratigraphic record

Pre-existing stratigraphic information

Few sea-level studies have previously been undertaken on the Pevensey Levels. However, the British Geological Survey (BGS) has collected borehole records from various positions across the Levels (see Fig. 3.2). Both auger and borehole samples were collected, some to depths of over 20m. Unfortunately, many of the records were not described in the detailed way required for accurate sea-level reconstructions, providing only broad sedimentary units. In addition to this, the top of each borehole was taken to be 'road level', which BGS stated to be –2 feet (*c.*+7 feet OD). This meant that accurate surface altitudes of the boreholes were not known and made a comparison between sites problematical. In order to overcome this, the 'road level' referred to by the BGS was calculated to be approximately equal to +2.23m OD, based on the survey results undertaken as part of this research. Using this level, the borehole records collected by the BGS are shown in Fig. 4.1.

Descriptions of the boreholes are divided into two sections, the first starting at the coast and progressing inland, and the second in an east to west direction. The Pevensey Bay core was the most coastal coring position. A borehole of 17 m was drilled which provided important information about the geology of the area. It can be seen that the lowest unit was clay, overlain by limestone. Above this, silt, sand and clay persisted until the sand disappeared and clay dominated. This was followed by over ten metres of marl, possibly indicative of a lake deposit. The upper units are then represented by a peat at approximately -1.5m OD, overlain by silty clay and capped by two gravel layers.


m O.D.
m depth
AH26
AH10
AH8
AH7
AH9
AH14
AH16
AH11


m O.D.
m depth
AH25 silts 0.5m
AH18 11m
AH12
AH20
AH22
AH21
AH4
AH3 10–12m
AH2 11.87m
AH23 Hooe Level
AH24 Old Rd Farm

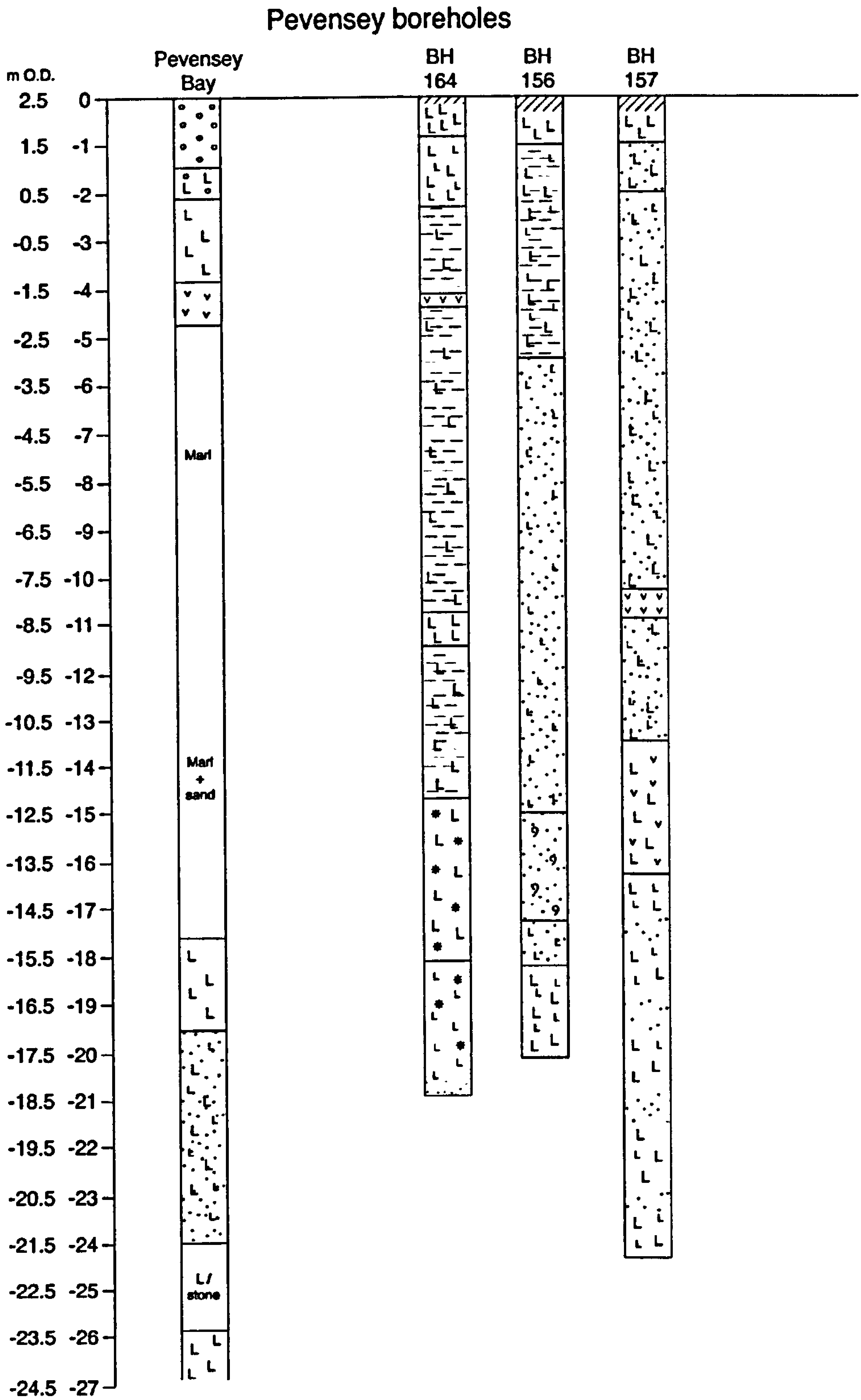


Fig. 4.1 BGS borehole data from the Pevensey Levels represented as an inland transect. Stratigraphic symbols are based upon the Troels-Smith classification (1955)

Three deep cores were taken further inland, near the Pevensey roundabout (see Fig. 3.2). BH164 showed a thin layer of peat at c. –0.5m OD with the remaining units mainly consisting of organic silty clay. BH156 did not reveal any peat layers, however, 5m of organic silty clay underlain by sand and silt was recorded. BH157 showed no evidence for a peat layer at *c.*0m OD but did reveal two deeper peat layers, the first at –8m OD and the second a clay and peat layer at –11.5m OD. Silt, clay and sand dominated the underlying units. These three cores were all taken in close proximity to one another, less than 500m apart, and the results are the first indication that the Levels show a very varied pattern of sedimentation.

AH25 and AH18 were sampled south of the A259, very close to some of the borehole locations collected in this research. Interestingly, no peat layer was recorded. Sandy silty clay with *part. test. molluscorum,* was the lowest unit recorded between depths of –9m and –4m. This unit was overlain by silty clay, with occasional sand lenses recorded. Further inland, AH12 and AH20 again did not reveal any buried peat layers although two organic clay layers were recorded in AH12, between depths of –1.75m and –2.25m and also –2.7 and –3.0m. The lower sediments were dominated by silty clay with some shell fragments.

At the most inland sites, where the land begins to rise, a variety of sediments were recorded. AH22 showed no buried peat layers or any organic units and was simply dominated by silty clay and some sand. AH21and AH4 revealed silty clay with *part. test molluscorum,* overlain by organic silty clay, capped by silty clay. AH3 however, showed organic silt overlain by silty clay, followed by a thin peat layer at c. 0m OD, capped by silty clay. Lastly, AH2 revealed two buried peat layers at c. –1m OD and at 0mOD, demonstrating again that the stratigraphy of the Pevensey Levels is quite diverse.

The remaining borehole locations broadly follow an east to west direction and again show a very inconsistent pattern across the Levels. AH26 was dominated by silty clay and showed no evidence of organic sediment. AH10 did not reveal a buried peat layer but did display an organic silty clay layer between an upper and lower silty clay layer at a depth between –1.75m and -2.50m. AH8 and AH7 revealed no organic deposits or buried peat layers. However, in AH9, a buried peat layer was recorded at c. 0m OD, between the upper and lower silty clay units, similar to the pattern in AH3. Lower organic silty clay was also recorded at c. -10m OD. AH14 and AH16, the most eastern sites, revealed a very similar pattern of deposition to each other showing a peat layer at –1.50m to –3.0m and a lower organic clay layer below –5m.

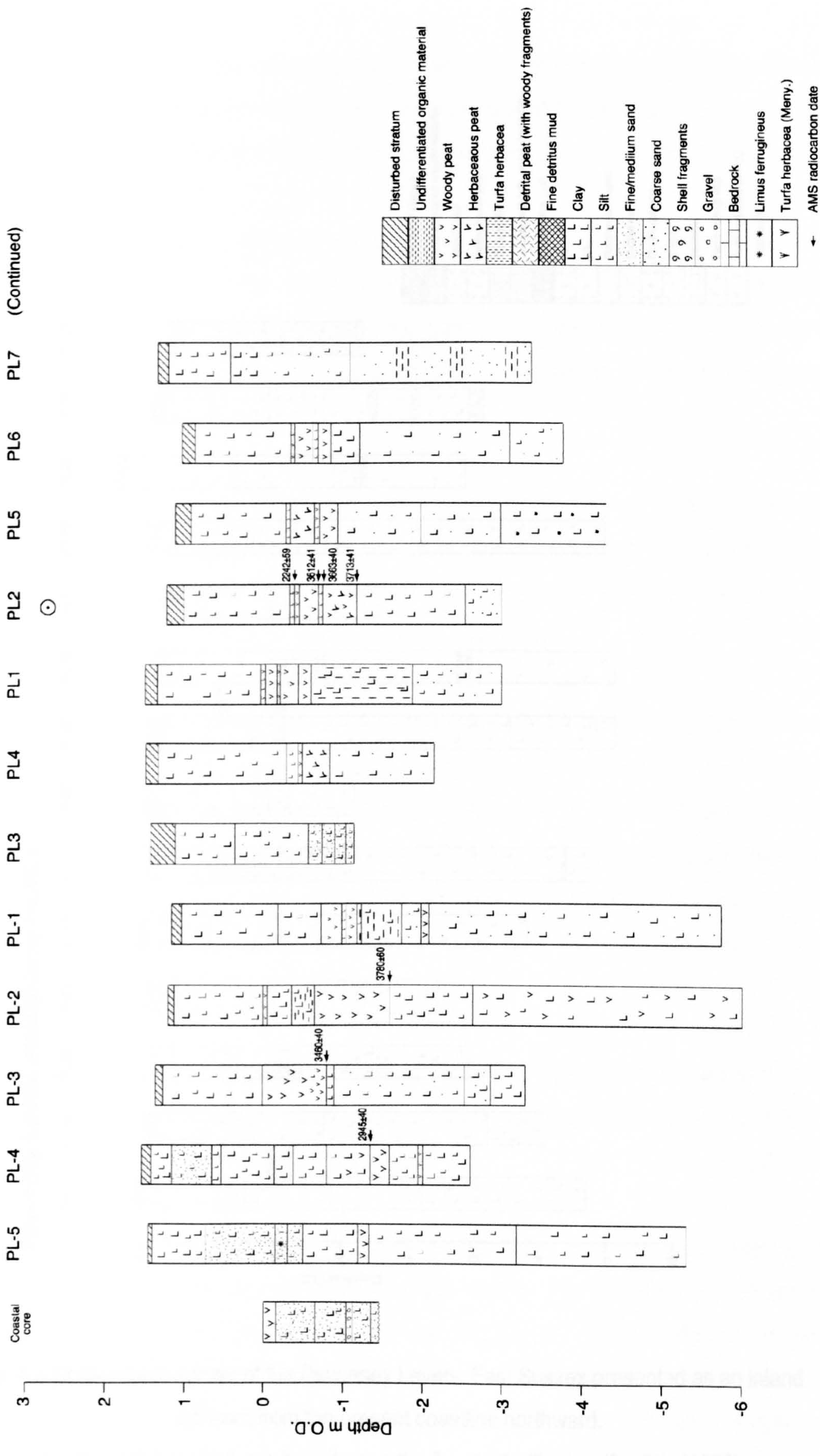
However, AH11 in the centre of the Levels showed no peat layer, only an organic silty clay layer between –1.75m and 2.5m, between the upper and lower silty clay units. The most easterly sites, AH23 and AH24 on Hooe Level, showed lower silty clay overlain by sand in AH23 and clay in AH24. The silty clay was overlain by sandy silty clay, which progressed into a thick organic deposit occurring around 0m OD. Once again the upper unit was silty clay, common across the Levels.

Stratigraphic data has also been collected by Parish (1996), who carried out a description of a single core from the Pevensey Levels. The study revealed intercalated peats, silts and clays with the presence of sand in some of the lower units. Details of Parish's study are not presented here since the precise location of the borehole is not known and many of the units were not sampled.

Stratigraphic survey of the Pevensey Levels, East Sussex

To supplement the existing data and add details to the upper part of the stratigraphy, a series of boreholes were collected from the Pevensey Levels, starting at the coast and progressing northwards until the land rose (refer to the map in Chapter Three Fig. 3.2). The stratigraphy present across the levels can be broadly divided into six units (see Fig. 4.2 and Table 4.1). However, not all of these units were found in all cores, in particular the buried peat layers, which varied greatly in thickness and distribution.

The lowest unit recorded during the stratigraphic survey at Pevensey was a sandy silty clay unit. This unit was consistent across the Levels, with some variation in the content of sand. The liquefied nature of the sediment made collection of this unit by both hand gouge and piston corer impossible. The deeper peat at around -8m OD recovered by the BGS, was not retrieved by the stratigraphic survey, since professional drilling would have been required to reach such depths. However, in cores PL-2 and PL28 it can be seen that some organic material was present in the lower sandy silty clay. In cores PL10 and PL21, the sand content of this lowest unit was much higher, once again highlighting the variable nature of the deposits across the Levels.


(Continued)
PL7
PL6
PL5
PL2
PL1
PL4
PL3
PL-1
PL-2
PL-3
PL-4
PL-5
Coastal core
2242±59
3612±41
3663±40
3713±41
3780±60
3460±40
2945±40
Depth m O.D.
3
2
1
0
-1
-2
-3
-4
-5
-6
Disturbed stratum
Undifferentiated organic material
Woody peat
Herbaceaous peat
Turfa herbacea
Detrital peat (with woody fragments)
Fine detritus mud
Clay
Silt
Fine/mediium sand
Coarse sand
Shell fragments
Gravel
Bedrock
Limus ferrugineus
Turfa herbacea (Meny.)
AMS radiocarbon date

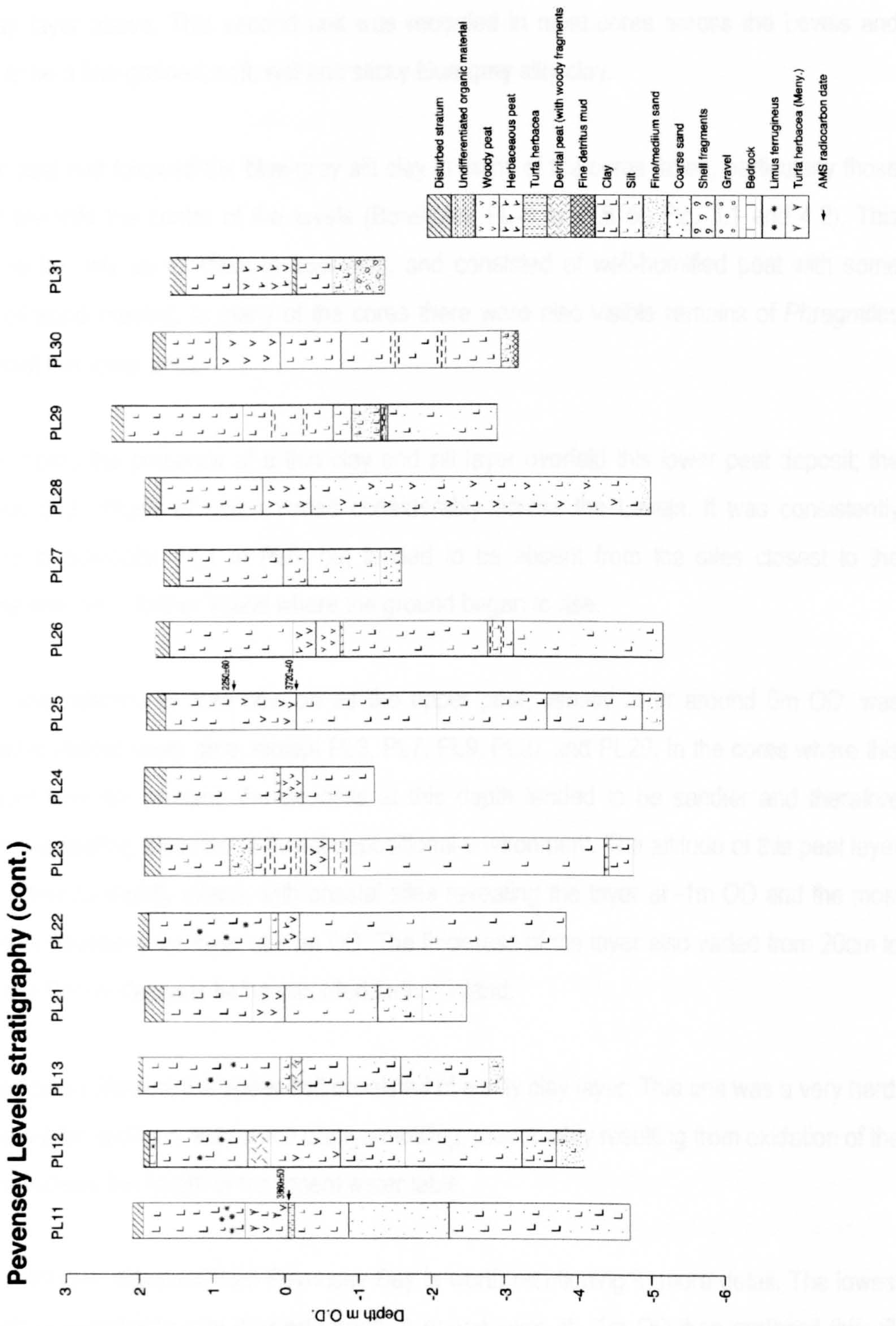


Fig. 4.2 Stratigraphic survey of the Pevensey Levels, East Sussex presented as an inland transect from the present coastline northward.

Stratigraphic symbols are based upon the Troels-Smith classification (1955)

The lower sandy silty clay unit gradually became less sandy, progressing in most cores into a silty clay layer above. This second unit was recorded in most cores across the Levels and tended to be a fine-grained, soft, wet and sticky blue-grey silty clay.

A lower peat unit followed the blue-grey silt clay in many of the cores taken, particularly those located towards the centre of the levels (Boreholes PL-1 to PL6 on Fig. 3.1 and 4.2). This tended to be only up to 15cm in thickness, and consisted of well-humified peat with some pieces of wood present. In many of the cores there were also visible remains of *Phragmites* throughout this lower peat.

In many cores the presence of a thin clay and silt layer overlaid this lower peat deposit; the thickness and altitude of which varied considerably across the Levels. It was consistently recorded in boreholes PL1 to PL6, but tended to be absent from the sites closest to the coastline and those further inland where the ground began to rise.

A peat unit, referred to from now on as the upper peat, usually at or around 0m OD, was recorded in almost every core, except PL3, PL7, PL9, PL27 and PL29. In the cores where this peat layer was not present, the deposits at this depth tended to be sandier and therefore coarser, suggesting a marine or fluvial depositional environment. The altitude of this peat layer sloped upwards slightly inland, with coastal sites revealing the layer at -1m OD and the most inland sites revealing the layer at +1m OD. The thickness of the layer also varied from 20cm to 70cm, with thicker deposits being recorded further inland.

In all samples collected, the upper unit consisted of a silty clay layer. This unit was a very hard, dry brown-grey sediment with some orange mottling, presumably resulting from oxidation of the sediment, above the height of the recent water table.

The coastal core collected from Pevensey Bay is worth mentioning in more detail. The lowest sediment recorded was silty clay with sand. A gravel layer at –1m OD then replaced this silt and clay. Above this, sandy silty clay returned and was capped by an undifferentiated peat layer. The gravel layer recorded here is presumably part of the current gravel beach barrier that exists across Pevensey Bay and has therefore not been included in the summary descriptions.

A single sample core was selected because it represented the most representative core across the Levels. The stratigraphy of the sample core (PL2) can be divided into six stratigraphic units (see Table 4.1). The presence of the two peat units were particularly important as they offer the potential to obtain four sea-level index points, two regressive and two transgressive. The sample core is described in detail because it is used as the basis for all further biostratigraphic divisions contained within this chapter.

Unit	Depth (m OD)	Stratigraphic description
PLVII	-0.33 – +1.21	**Silty clay** A very hard brown grey part silt part clay layer – showing signs of oxidation above the water table
PLVI	-0.37 - -0.33	**Transition layer**
PLV	-0.66– -0.37	**Upper Peat** A well decomposed woody peat layer with large pieces of wood present at the lower contact
PLIV	-0.74– -0.66	**Clay and silt layer** A very thin layer separating the two peat layers
PLIII	-0.91– -0.74	**Lower Peat** Thin layer of well humified peat, often exhibiting remains of *Phragmites* and wood
PLII	-1.34 – -0.91	**Lower silty clay** Very fine, soft wet and sticky sediment, blue-grey in colour
PLI	-2.29 – -1.34	**Sandy silty clay** Silty clay layer showing the presence of sand

Table 4.1 Stratigraphy of the sample core collected from the Pevensey Levels

Mid- to late-Holocene sea-level changes at the Pevensey Levels based upon the stratigraphic descriptions

In order to gain an understanding of the depositional environment without the aid of the biostratigraphic data, a tentative interpretation based upon the stratigraphic alone is presented. An amalgamation of the BGS data and the borehole data collected as part of this project allows tentative conclusions about past sea-level changes to be made. The lowest unit recovered by the BGS was a deep peat layer. The presence of such a layer could indicate a low sea-level throughout the early-Holocene, with the change to the sandy silty clay representing a fairly rapid marine transgression. However, due to its spatial inconsistency across the levels and the fact that it was not recovered by the stratigraphic survey undertaken as part of this research, few conclusions can be drawn at this stage.

Unit PLI: Sandy silty clay

The lowest unit consistently recorded across the Levels was the sandy silty clay. This mixture of sand, silt and clay indicates that the area was probably inter-tidal at this time, possibly a sand or mud flat environment. The fine-grained silt and clay is usually indicative of calm, shallow water, but the presence of sand suggests that there was a strong tidal influence, and flooding at high tide was likely to have taken place.

Unit PLII: Lower silty clay

The transition into the silty clay layer (Sample core unit PLII), indicated that the area experienced a gradual change toward deposition under shallower and calmer water. A similar unit recorded at Romney Marsh (Long & Innes, 1993) was attributed to a progressive reduction in water depth and a reduction in the wave and tidal energy.

Unit PLIII: Lower peat

A further decline in sea-level was implied by the development of the lower peat layer (Unit PLIII). The peat was well humified signalling that it had been above MHWST for much of the time. Visible remains of *Phragmites*, usually found at or above HAT (Zong, 1997), suggest that the unit is probably indicative of a high marsh deposit. It is likely that differences in the compaction of the sediments have taken place, which could explain the variation in the altitude of the peat deposits. Research undertaken on the nearby Willingdon Levels, Eastbourne (Jennings, 1985; Jennings & Smyth, 1987, 1990) did not suggest the presence of this lower peat at either Lottbridge Drove or Langney Point (refer to Chapter 2.2 for details). However, a similar peat layer has been recorded at Romney Marsh (Long & Innes, 1993).

Unit PLIV: Clay and silt

The deposition of unit PLIV, a silty clay with some sand, suggests a possible rise in relative sea-level. A similar unit was recorded at Lottridge Drove (Jennings, 1985) between –6.08m and +0.4 m OD. This depth range covers the altitude that both the peat units were recorded at Pevensey.

Unit PLV: Upper peat

The onset of the upper peat at Pevensey (Unit PLV) should signal the return to freshwater or terrestrial depositional, indicating a relative fall in sea-level. Similar timings to peat development have been recorded at Lottbridge Drove (Jennings, 1985) and at Romney Marsh (Long *et al.*

1998). Whether a regional fall in relative sea-level can be detected should become clear once AMS radiocarbon dates are obtained.

Unit PLVI Transition and PLVII: Silty clay

The hard, oxidised silty clay found in the uppermost unit PLVI implied a return to shallow estuarine conditions, probably not unlike the conditions present today. Once again, this unit appears to be similar to the uppermost sediments found elsewhere in south east England including both Romney Marsh (Long & Innes, 1993, 1995; Long *et al.* 1998) and Lottbridge Drove (Jennings & Smyth, 1987, 1990).

For the purpose of a sea-level reconstruction, the stratigraphic data alone do not provide sufficient information about the depositional environments under which the seven main stratigraphic units at the Pevensey Levels were laid down. It is already possible to make several comparisons between the stratigraphy of the Pevensey Levels and that of other sites along the south coast of England, most notably sites on Romney Marsh and Lottbridge Drove. However, in order to establish the precise relation to water level of the transgressive and regressive overlaps and compare the findings at Pevensey to the other sites, the biostratigraphic data were analysed.

4.2 Pollen data for the Pevensey Levels, East Sussex

Pollen samples were taken from the stratigraphic boundaries and throughout the two peat layers in the sample core (PL2). In pollen analysis it is standard to assign pollen assemblage zones to the diagram to indicate the major shifts in the pollen preserved over time. However, in this study it was not beneficial to assign such zones because the study was not attempting to reconstruct the vegetation history of the Pevensey Levels and the sampling intervals are very uneven. The zones represented on the diagram by the dashed lines therefore mark the lithostratigraphic boundary changes. The pollen taxa in Fig. 4.3 are presented as percentages of total land pollen and have been divided into trees, shrubs, herbs, saltmarsh indicators, aquatics and spores.

Six stratigraphic zones have been assigned to the Pevensey Levels sample core based on the lithostratigraphic units. Unit PLI, the lowest unit recorded at Pevensey and the sample core was dominated by sand and no pollen was preserved within this unit, as would perhaps have been expected. The silty clay unit (unit PLII) above this also contained no pollen record, until just below the stratigraphic boundary with unit PLIII.

Unit PLIII: Lower peat (-0.91m — -0.74m OD)

This stratigraphic unit can be subdivided into two phases. The first phase contains the transition from the lower silty clay to the lower peat layer (Unit PLIII), which is marked by the sudden appearance of pollen, probably an effect of differential preservation. Just below the boundary at -0.93m OD (2.14m depth) no pollen was preserved. However, at –0.91m OD (2.12m depth) 16% trees and 80% Gramineae was recorded suggesting an open ground environment. The second phase is marked by a slight decline in tree pollen until –0.87mOD (2.08m depth) where a marked increase in *Alnus*, a species known to tolerate water-logged soils and damp woodlands, which suggests that the area had become less influenced by marine activity. However, it must be noted that according to Waller (1993) *Alnus* grains are resistant to decay and therefore may be over-represented in the pollen sum. Corylus is intermittently present throughout the unit. Values of *Osmunda* reached 10%, suggesting that the area may have dried out for a short time (Long & Innes, 1993). However, the constant levels of Gramineae pollen suggest the site remained a fairly open environment. The presence of *Artemesia cf.maritima* and *Myriophyllum* show that a water body was nearby, which may have been freshwater; but could possibly indicate the first signs of a rise in relative sea-level. These pollen types continued to dominate the record until the stratigraphic boundary at –0.74m OD (1.95m depth) where clay and silt replaced the peat.

Unit PLIV: Clay with some silt (-0.74m — -0.66m OD)

It is not common for pollen to be preserved in many minerogenic layers, although in this case small amounts of organic matter were present just across the boundary, which enabled pollen to be extracted from the matrix. An increase in open ground pollen can be seen with low values of *Plantago lanceolata* being observed, indicating disturbed ground. *Alnus* continued to dominate the record, with increased amounts of *Corylus*, another species known to tolerate moist ground.

Just below the boundary with the upper peat layer, in sample –0.68m OD (1.89m depth), pollen was preserved in the minerogenic sample. This marked a significant change in the pollen record with Chenopodiaceae being recorded, often an important salt marsh indicator. Gramineae pollen was also recorded, reaching 40% of the total pollen. Values of *Alnus* were low, with tree pollen being replaced by *Corylus.* The occurrence of small amounts of *Picea* suggests that the pollen grains were transported into the area, most likely water-borne.

Unit PLV: Upper peat (-0.66m — -0.37m OD)

The pollen record shows three clear phases throughout this upper peat unit. Phase 1, the transition into the upper peat layer had suggested deposition under a gradually falling sea-level, possibly the formation of a salt marsh deposit. Unfortunately, the first complete peat sample was non-polleniferous, only four pollen grains were recorded, two Gramineae and two *Osmunda*, making it difficult to draw any conclusions. Low pollen values continued to be a problem throughout the unit until –0.60m OD, with the maximum count reaching sixteen. This is a common problem within the study of coastal peat deposits, where the source of the local pollen and the causes of shifts in wetland vegetation are often subject to much debate (Waller, 1993).

Phase 2: At –0.60m OD (1.81m depth) the preservation of pollen improved. Once again *Alnus* grains dominated the count, accounting for 45% of the total pollen. *Betula* was also present in significant quantities, a species common to woodland edges and bogs. *Osmunda, Artemesia cf. maritima* and *Myriophyllum* were also present again, as was *Potentilla*, a species also commonly found on the edge of woodlands and in open grassland. These pollen types continued to be present throughout the unit, with percentages varying slightly but not significantly.

Phase 3: At -0.48m OD (1.69m depth) a major change in the pollen can be seen. A sharp rise in *Osmunda* occurred which continued until –0.42 m OD (1.63m depth). *Typha angustifolia* (reedmace) was also recorded at this depth, a plant commonly found near slow moving freshwater and alongside ditches. *Osmunda* values decreased and an increase in the tree species *Alnus* and *Betula* was seen, rising to 20% and 40% respectively. This indicated a shift to more freshwater conditions. Gramineae was also present in significant quantities once more. Previous research (Long & Innes, 1993; 1995) suggests that high levels of tree pollen are often found at back-marsh sites. Pollen from drier, upland areas contributes to the pollen record, whereas at mid- and fore-marsh sites the local wetland vegetation dominates the pollen record (Long & Innes, 1995). At Pevensey, it is therefore possible that the high levels of *Alnus* and *Betula* seen throughout the upper peat, reflect pollen blown-in from the edges of the estuary. Another major shift can be seen at –0.40m OD (1.61m depth) when Chenopodiaceae again appeared in substantial quantities, with 10% being recorded at this depth, increasing to 30% in PLVI. Gramineae values remained high, varying from 20% to 40%, and *Alnus* and *Betula* continue to be present throughout. The pollen suggests the presence of a salt marsh, which is also shown by the change in the sediment type, reflecting a shift from freshwater to brackish water conditions.

Unit PLVI Transition: Upper peat to Upper silty clay (-0.37m – -0.33m OD)

This thin silty peat layer marks the transition from the upper peat to the silty clay. This is an important stratigraphic layer because the pollen record suggests that a salt marsh was present at the time of sediment deposition. Chenopodiaceae rises to 30% at the stratigraphic boundary with Gramineae accounting for just over 40% of the total pollen sum. Above the stratigraphic boundary at -0.35m OD (1.56m depth) *Betula* and *Corylus* pollen increased, however Graminieae and Chenopodiaceae were both still present. It is likely that this silty peat layer represents the existence of a salt marsh, with the tree pollen provided from the edges of the estuary.

Unit PLVII: Upper silty clay (-0.33 – +1.21m OD)

The first sample above the stratigraphical boundary contained a few pollen grains of Gramineae and *Osmunda,* suggesting an open but disturbed environment. However, since counts were low (often less than 50 grains) it is not possible to assign an environmental habitat based on pollen. The remaining samples taken from this unit contained no preserved pollen grains.

The pollen record provided useful information about the vegetation changes that occurred at the time of organic sediment deposition. Table 4.2 provides a summary of the major pollen types recorded within each stratigraphic unit.

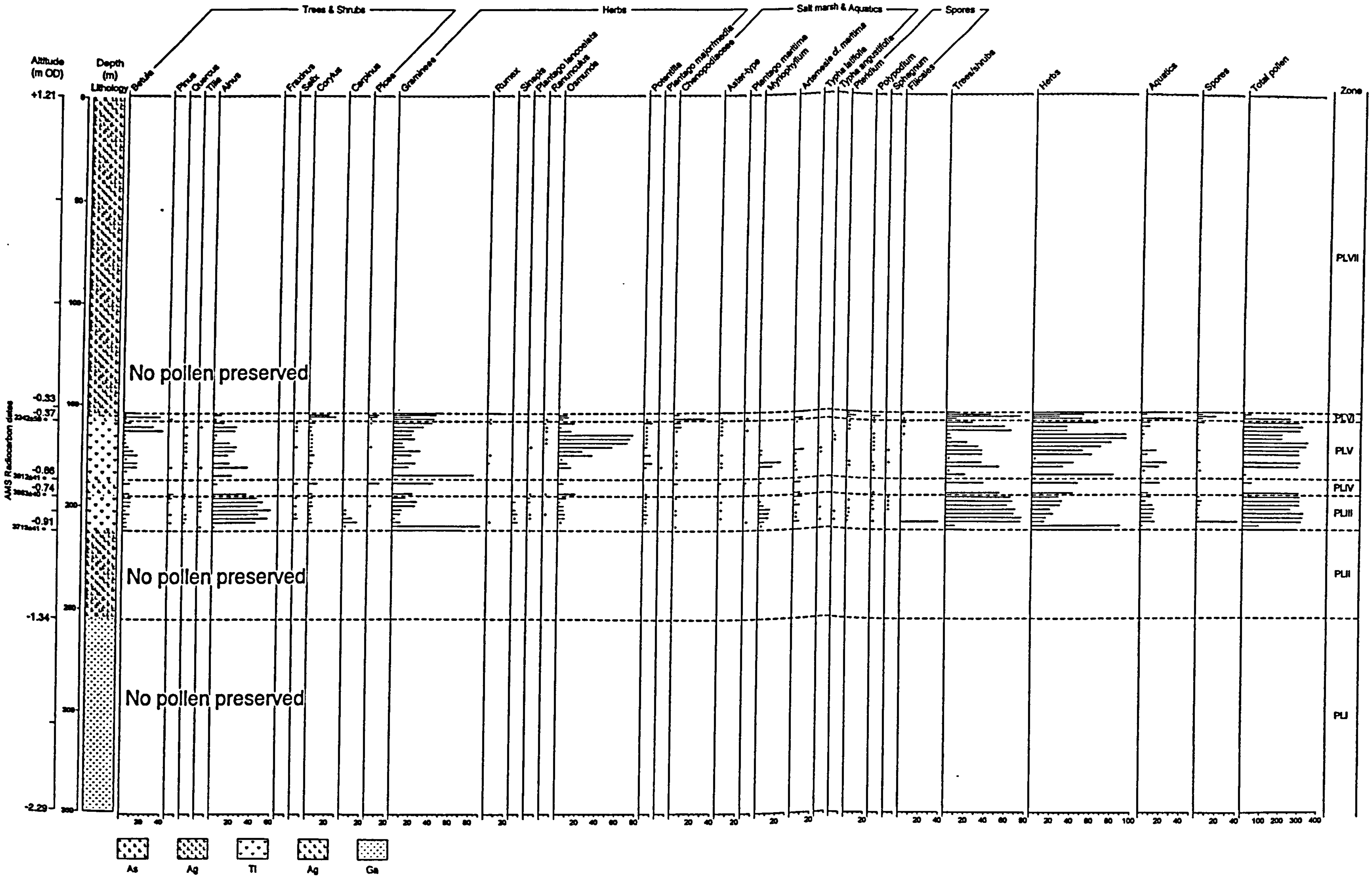


Fig. 4.3 Diagram of pollen data for the Pevensey Levels, East Sussex
Zones are based upon the stratigraphic boundary divisions and stratigraphic symbols follow the Troels-Smith classification (1955). The data are presented as a percentage of total land pollen and is divided into trees, shrubs, herbs, saltmarsh, aquatics and spores. The end columns present the total values of the pollen data.

Unit	Stratigraphy	Biostratigraphy	Environment
PLVII	Upper silty clay		No pollen
PLVI	Transition Silty peat	Lower samples dominated by Chenopodiaceae and Gramineae Shift to poor pollen preservation and a mixture of open ground species e.g. *Rumex, Artemesia cf. maritima*, *Aster*-type and Gramineae	Saltmarsh → Open scrub
PLV	Upper peat	Phase 1: No pollen preserved Phase 2: Onset is marked by open ground, moisture favouring species *Alnus*, *Osmunda, Artemesia cf. maritima* and *Corylus* again Phase 3: Just below the upper boundary a marked increase in Chenopodiaceae is seen to occur, this time with Gramineae and *Alnus* dominating	Phase 2: Open ground, moisture favouring trees Phase 3: Increased marine influence (saltmarsh)
PLIV	Clay with some silt	Upper contact contained first presence of Chenopodiaceae No pollen preserved	Cultivated land
PLIII	Lower peat	Phase 1: Dominance by Gramineae Phase 2: A shift to wetland vegetation including *Alnus*, *Osmunda*, *Artemesia cf. maritima* and *Corylus*	Phase 1: Open Phase 2: Wetland
PLII	Lower silty clay		No pollen
PLI	Sand silt and clay		No pollen

Table 4.2 Summary of palynological data based upon the stratigraphic boundaries

A series of vegetation shifts can be seen from the descriptions of each stratigraphic unit. What is of most interest for this research is the influence that rising or falling sea-level has had upon the area. Although it is difficult to draw any firm conclusions about past sea-levels based solely on palynological data, it is possible to observe the changes in wetland vegetation, thus providing a tentative history of sea-level change.

The gradual shift from the lower silty clay (Unit PLI) to the lower peat (Unit PLII) suggested a gradually falling relative sea-level. The pollen suggested that although the area may have become terrestrial, the area was still subject to considerable wetting periods. Whether or not this was flooding by the sea is not possible to state at this stage. The presence of *Myriophyllum* indicated the close proximity of a freshwater body and *Artemesia cf. maritima* suggested that the area was regularly flooded at high tide. The area then appeared to become increasingly terrestrial, with rises in the percentages of tree pollen, indicating that a fall in relative sea-level had taken place. Towards the top of the peat deposit the pollen suggests an opening up of the woodland, indicating a very low sea-level at this time. The shift from peat (Unit PLIII) to silty clay (Unit PLIV) resulted in a poor preservation of pollen grains, indicating a marine influence once more. At the contact with the upper peat unit the pollen record suggested a return to an open wetland environment, implying a fall in relative sea-level had taken place.

The onset of the upper peat (unit PLV), indicates that either a significant fall in sea-level had taken place, probably over a fairly short time period as the stratigraphic boundary shift was relatively abrupt but did not appear to be erosive, or that barrier emplacement had occurred. The pollen record showed this relative fall in sea-level persisted throughout the peat layer, with a shift from woodland to more open ground and then back to woodland conditions being observed. Towards the top of the peat layer sea-level began to rise, marked by the appearance of salt marsh indicators. Open and salt marsh conditions prevailed until the deposition of the upper silty clay, when the pollen concentration declined, suggesting that fully marine conditions had returned.

Throughout the sample core, pollen analysis was only successfully undertaken on the peat deposits. This was because the pollen was absent from the minerogenic deposits. Diatom and foraminiferal analyses were more effective in minerogenic sediments were also performed. Therefore pollen samples were not collected from the minerogenic deposits since most would have yielded more results and even if pollen had been preserved the data would have to be accepted with caution.

4.3 Diatom data from the Pevensey Levels, East Sussex

Diatom data were collected from each stratigraphic layer of the sample core, although preservation of the diatom valves was generally poor throughout most of the units and it was not possible to achieve samples containing counts of 300 valves for every sample. Once again the zones and descriptions are based upon stratigraphic changes. Fig. 4.4 presents the diatom data and Table 4.3 provides a summary of the results for each stratigraphic unit.

Unit	Stratigraphy	Biostratigraphy	Environment
PLVII	Upper silty clay	No diatoms preserved	
PLVI	Transition Silty peat	*Paralia sulcata* and *Pseudopodosira westii* with *A. delicatula* plus some freshwater species *Pinnularia* sp. *Navicula peregrina* and *C. keutzighiana*	Low marsh at around MHWST
PLV	Upper peat	No diatoms preserved	
PLIV	Clay with some silt	Few diatoms preserved	Unclear
PLIII	Lower peat	Mixture of species including *P. sulcata, P. westii, Fragilaria brevistriata* and *A. delicatula* plus *Cycoltella keutzighiana,* and *Pinnularia*	Marine tidal flat species washed-in to a freshwater environment
PLII	Lower silty clay	*Paralia sulcata* and *Acnanthes delicatula*	Tidal flats – low marsh near to MHWST
PLI	Sand silt and clay	Dominated by *Paralia sulcata, Psudeopodosira westii* and *Opephora schwartzii* with some brackish species present in low quantities *Diploneis smithii* and *Tryblionella. navicularis*	Tidal flats between MLT and MHWST

Table 4.3 Summary of diatom data for the Pevensey Levels, East Sussex

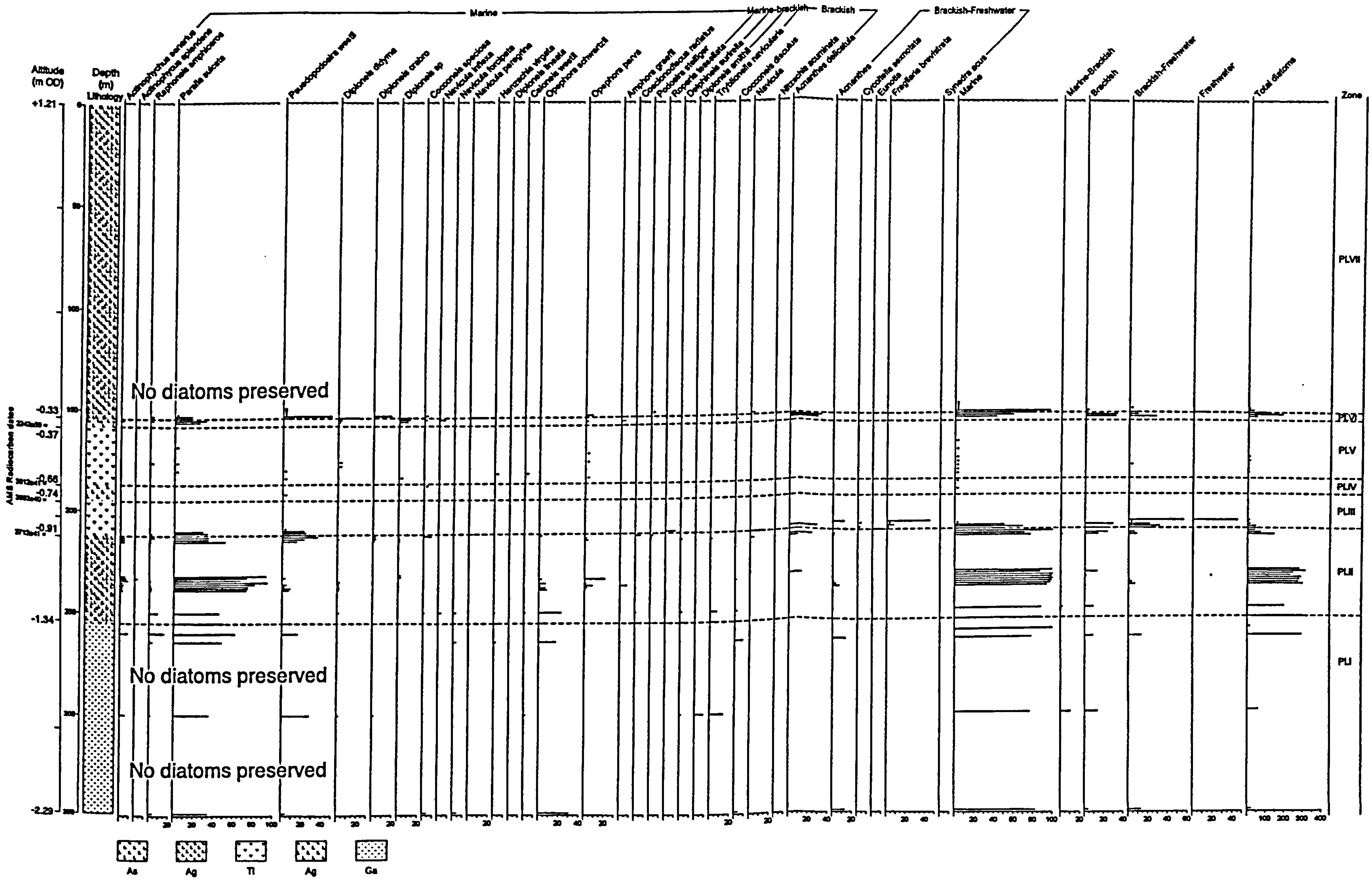


Fig. 4.4 Diatom data from the Pevensey Levels, East Sussex
Zones are based upon the stratigraphic boundary divisions and stratigraphic symbols follow the Troels-Smith classification (1955). The data are presented as a percentage of total diatoms and is divided into marine, marine-brackish, brackish, brackish-freshwater and freshwater.

Unit PLI: Sand (-2.29m OD — -1.34m OD)

The marine species *Paralia sulcata, Pseudopodosira westii* and *Opephora schwartzii* were the most well preserved species in this unit. In the lowest sample taken, diatom preservation was quite poor; less than 50 valves. Preservation improved slightly in the upper samples, with one sample reaching a count of 200 tests. Despite the relatively low number of tests, *P. sulcata* was seen to dominate, accounting for 35% of the total diatom sum. *P. sulcata* is a polyhalobous tychoplanktonic species, commonly recorded along the south east coastlines of Britain (Hendey, 1964). It is probably one of the most well researched species, since it is found along most British coastlines. In modern day assemblages it is frequently observed on sandflats (Zong & Horton, 1998, 1999) and was assigned to the "Melosira-sulcata Group" (Vos & de Wolf. 1988). Zong & Horton (1999) noted that it occurred most frequently between MTL and MHWST with a Standardised Water Level Index (SWLI) ranging between 220 and 290, where MTL has a SWLI of 200 and MHWST is 300. However, because the diatom possesses filamentous chains, it is one of the species that is subjected to washing-in and is nearly always found not *in-situ*. The appearance of *Actinophytchus senarius*, also part of the "Melosira-sulcata Group" confirmed that the sediment was a marine deposit, most likely a sandflat deposit. The appearance of *Acnanthes delicatula* and the occasional presence of other brackish species such as *Tryblionella navicularis*, a mesohalobous species common to mudflats, mark a change in the depositional environment towards the top of the unit. However, it must be noted that percentages of these species were low, less than 5%.

Unit PLII: Lower silt and clay (-1.34m OD — -0.91m OD)

The lower silty clay unit contained a well-preserved diatom record which allowed full counts to be made (300 valves). Samples at the lower stratigraphic boundary once again revealed a dominance by the marine species *P. sulcata, Raphoneis amphiceros* and *O. schwartzii* with the brackish species *T. navicularis* appearing in low but significant quantities. A slight shift was then seen in the samples taken from the centre of the unit (-1.09 — -1.19m OD). *A. senarius* peaked at 10% of the total diatom sum and *P. westii, O. schwartzii* and *Opephora parva*, all marine species, each account for between 10 and 20% of the total. Towards the upper boundary another shift in the diatom species occurred. *P. sulcata* continued to dominate, accounting for 40% of the total diatom sum, but is now accompanied by an increase in *P. westii* which reached up to 40% at the boundary. Also appearing at –1.12m OD for the first time in percentages greater than 5% was *Acnanthes delicatula*, a mudflat species found around MLT

(Zong & Horton, 1998), which accounted for 20% of the diatom sum, indicating a fall in relative sea-level.

Unit PLIII: Lower peat (-0.91m — -0.74m OD)

Diatom preservation within this unit was poor due to the organic nature of the sediment. Only the lowest samples contained any diatom frustules and even then counts only reached fifty. *P.sulcata* and *P. westii* were present in significant quantities suggesting the area was still under marine influence, and the presence of *Acnanthes delicatula* indicates that the area may have been a mudflat or low marsh. However, several freshwater species were also present, showing a slight freshening upwards and a possible sea-level fall, indicating deposition above MHWST.

Unit PLIV: Clay with some silt (-0.74m — -0.66m OD)

Despite this unit being inorganic very few diatoms were found preserved, some broken fragments were present but it was not possible to count these because less than half the frustule was present. The origin of this deposit cannot be ascertained from the diatom data alone.

Unit PLV: Upper peat (-0.66m — -0.37m OD)

Throughout this unit few or no diatoms were preserved.

Unit PLVI Transition: Silty peat (-0.37m — -0.33m OD)

Once again *P. sulcata* and *P. westii* appeared in high frequencies suggesting a marine influence. *Acnanthes delicatula*, a tidal flat species was also present accounting for 30% of the total diatom count. However, some freshwater species such as *Pinnularia* sp. and *C. keutzighiana* were also present, indicating a very mixed diatom group. It is possible that reworking of the sediment in the intertidal zone allowed freshwater species, normally found in the upper marsh sediments, to be recorded.

Unit PLVII: Upper silty clay (-0.33 — +1.21m OD)

Diatom preservation was poor throughout this unit, meaning only very low counts were possible. Although *P. sulcata* was present occasionally, data based solely upon this species can not be trusted, due to the problems of washing-in previously discussed.

The diatom data from the Pevensey Levels allowed further information about the depositional nature of the inorganic sediments to be obtained. The record revealed that the lowest unit was a sandflat, deposited between around MTL. This revealed a strong marine influence at this time. A slight fall in sea-level must have then occurred, seen near the upper stratigraphic contact, in order for low marsh species, such as *A. delicatula* to have appeared in significant quantities. Throughout the lower peat (Unit PLIII) diatom preservation was poor, suggesting that maybe the sediment had been oxidised allowing dissolution of the frustules (Mayer *et al.* 1991) and a fall in relative sea-level had taken place. Unit PLIV above this contained too few diatoms to provide any information about the depositional environment and the upper peat layer also provided no data, making a conclusion about the relative sea-level at this time difficult. However, the presence of the upper peat layer would imply another relative fall in sea-level. The silty peat transitional layer revealed a high marine influence indicating that tidal flats were present, suggesting a relative rise in sea-level had occurred. The upper silty clay (Unit PLVI) contained no diatom valves. This is a commonly encountered problem in sea-level research with similar findings at both Romney Marsh (Long & Innes, 1993) and Cowpen Marsh (Zong & Horton, 1998).

Application of a diatom-based transfer function to data from Pevensey

In order to validate the diatom data presented above and reconstruct palaeo-tidal-level, the results were then further analysed using a diatom-based tidal level transfer function (Zong & Horton, 1998, 1999). This transfer function was created using modern day diatom assemblages collected from six sites in the north and east of England. Standardised Water Level Indices (SWLI), a measure of altitude relative to the tidal frame, were established in order to allow inter-site comparisons. The results showed that the tolerance-downweighted, weighted-average performed marginally better than the ordinary weighted average (Zong *pers. comm.*). This meant that the root mean squared error prediction (RMSEP) was lower and the squared correlation (r^2) value was higher. Full details of the calibration dataset that was used are contained in Chapter Three. The transfer function was then applied to the fossil data collected from the Pevensey Levels providing the results detailed in Table 4.4 and Fig. 4.5. where MHWST has a SWLI of 300. In order to establish the altitude of the sample relative to OD, the SWLI were back-transformed using local MHWST and MTL (see Equation 4.1). The full details of the transfer function may be found in Appendix III.

$$\left[\frac{(Xab-200)}{100}\times(MHWST-MTL)\right]+MTL=Aab$$

Equation 4.1 Back-transformation of SWLI to tidal level Where *Xab* equals SWLI and *Aab* equals tidal level (After Zong & Horton, 1998)

Depth (cm)	WL-(WAT)	Back transformed Depth OD	Reference Water Level (MHWST +/-)
153	240	0.94	-1.71
154	282	2.12	-0.53
155	280	2.08	-0.57
156	315	3.09	0.44
211	326	3.38	0.73
212	310	2.94	0.29
213	240	0.94	-1.71
214	238	0.87	-1.78
215	271	1.83	-0.82
232	242	0.99	-1.66
233	241	0.96	-1.69
234	231	0.67	-1.98
235	238	0.88	-1.77
236	238	0.89	-1.76
237	236	0.83	-1.82
238	237	0.86	-1.79
239	238	0.90	-1.75
250	239	0.90	-1.75
255	242	1.01	-1.64
264	239	0.91	-1.74
300	261	1.53	-1.12
350	238	0.87	-1.78

Table 4.4 Diatom-based transfer function data from the Pevensey Levels, East Sussex WL-(WAT) refers to the SWLI as predicted by the transfer function

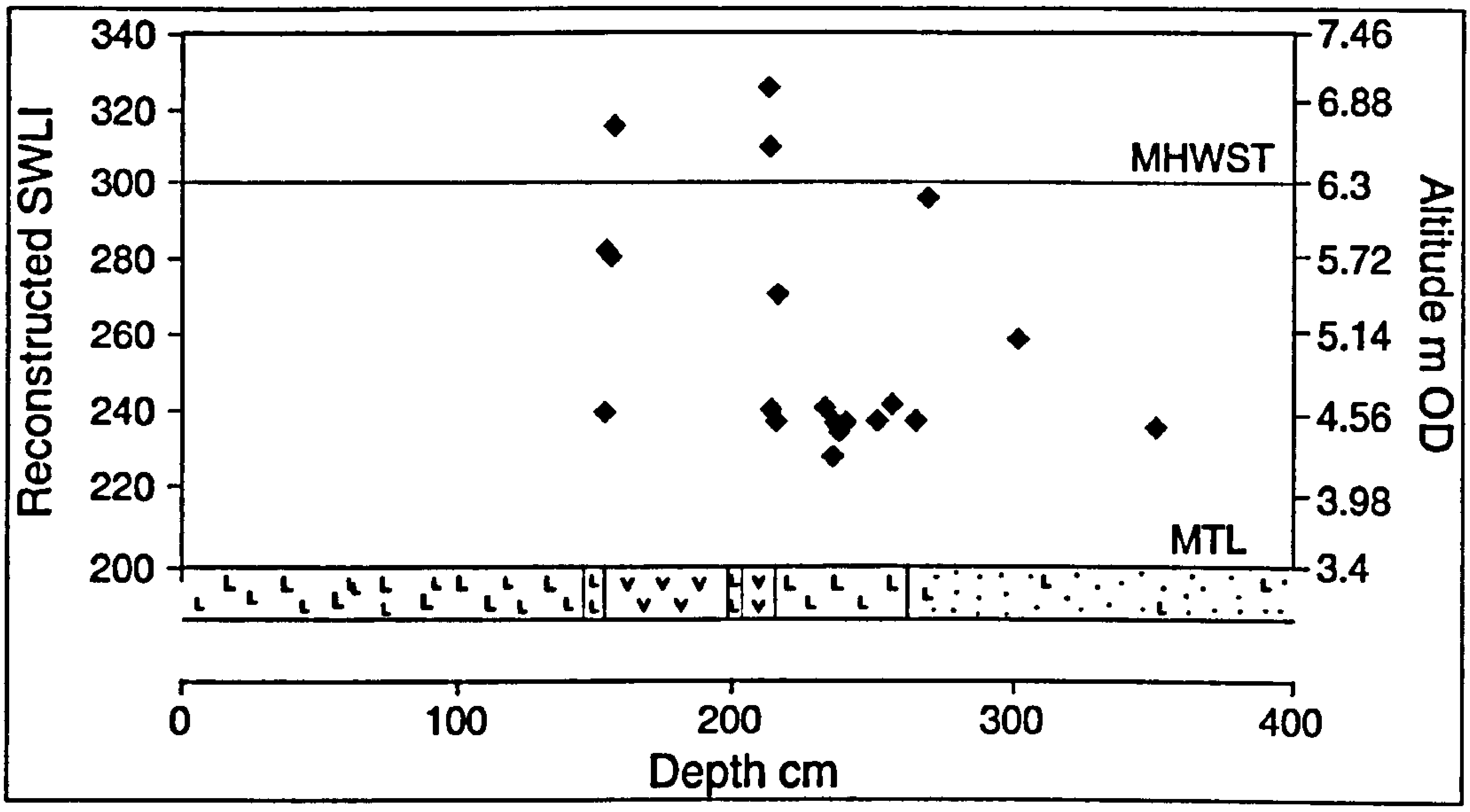


Fig. 4.5 Graph to show the value of predicted SWLI against depth (cm)
Where MHWST is assigned an index of 300 and MTL has an index of 200.

The results showed that most of the samples fell between MTL and MHWST, that is they had a SWLI of between 200 and 300. However, three of the samples lay above MHWST, with a SWLI above 300. Two of these higher points marked the lower regressive overlap (211-212cm depth) and the third marked the upper transgressive overlap (156cm depth), which would be expected to lie at or around MHWST. Once back-transformed, using Equation 4.3.1.1, the sample taken from 211cm depth may be assigned a tidal level of MHWST +0.73m and the sample taken from 212cm depth a tidal level of MHWST +0.29m. The upper sample at 156cm depth was assigned a tidal level of MHWST +0.44m. This placed deposition of the peat layer at a tidal level above MHWST, but below HAT as would be expected.

The transfer function predicted that all the samples that were obtained from below 212cm depth, from within the silty clay (Unit PLII), had a SWLI less than 300 but greater than 200, which places them at approximately MHWST –2m, slightly above MTL. The samples taken from above 156cm depth, also fell below MHWST but above MTL, confirming that the diatoms recorded from most of the core reflected an intertidal habitat as suggested by their known affinities. This however will not be true for the marine planktonic species.

It is important to note that the DBTF appeared to under-perform, probably because many of the diatom species recorded at Pevensey were not part of the training set obtained from north east England. At Pevensey only 17 of the 30 species recorded were included in the training set. The species not contained in the modern set included both freshwater and marine species, for example *Diploneis crabro* (Dc), a marine species that was found in abundance at Pevensey (up to 20%). Several other important marine species were also absent from the training set, including *Opephora marina*, *Pseudopodosira westii* and *Hantzschia virgata*. More critically however, many of the freshwater species recorded at Pevensey were not in the training set including, *Synedra acus*, *Cyclotella keutzighiana* and *Cyclotella radiosa*.

If the data at each of the stratigraphic contacts is examined it can be seen that there is a huge variation in the application and thus effectiveness of the DBTF. At the lower regressive overlap at 215cm depth, 81% of the species encountered were present in the training set, which should produce reliable results. At the uppermost transgressive overlap at 156cm depth, 94% of the species encountered were present in the training set, which should again produce reliable results. However, at the transgressive overlap at 198cm depth and the regressive overlap at 190cm there were no diatoms present in the dataset, which meant that applying the DBTF was impossible.

The results of the DBTF identified clear shifts in the depositional environment, marked by a regressive overlap at around 212cm depth (nearest diatom sample 215cm depth) and a transgressive contact at around 156cm depth. The results revealed the value of employing such transfer functions to fossil sequences, thus allowing sea-level index points to be validated by established in the palaeo-tidal level. However, it also highlighted the need to restrict the application of such transfer functions to datasets that contain similar diatom species to those contained in the training set.

The limitations of DBTF discussed above, therefore make the use of this particular transfer function too unreliable. Unfortunately, it was not possible to use the findings of the DBTF to reconstruct the tidal levels from Pevensey. The discussions which follow in the remaining chapters do not reply upon the findings of the DBTF, but are based upon the findings of the biostratigraphic data collected as part of this research.

4.4 Foraminiferal data from the Pevensey Levels, East Sussex

The foraminiferal counts from the Pevensey Levels have been divided into zones based upon the stratigraphic units. Fig. 4.5 shows the data presented as a graph and Table 4.5 provides a summary for each stratigraphical unit.

Unit	Stratigraphy	Biostratigraphy	Environment
PLVII	Upper silty clay	No samples taken	
PLVI	Transition Silty peat	*J. macrescens* and *A.beccarii*	Salt marsh
PLV	Upper peat	No foraminifera preserved	Freshwater
PLIV	Clay with some silt	High frequency of *A. beccarii* and *J. macrescens*	Hyposaline estuary or salt marsh
PLIII	Lower peat	Few foraminifera recovered One sample contained *J. macrescens and H. germanica*	Salt marsh around HAT or mudflats
PLII	Lower silty clay	Initially dominated by *A. beccarii* with *T. inflata* Shift to dominance by *N. depressulus* with *J. macrescens*	Hyposaline estuary Shift to inter-tidal or high marsh setting
PLI	Sand silt and clay	Few foraminifera recovered – *A. beccarii, T. inflata, E. williamsonii* and *N. depressulus* all present in low quantities	Hyposaline estuary, intertidal sand flats

Table 4.5 Summary of the foraminiferal data from the Pevensey Levels, East Sussex

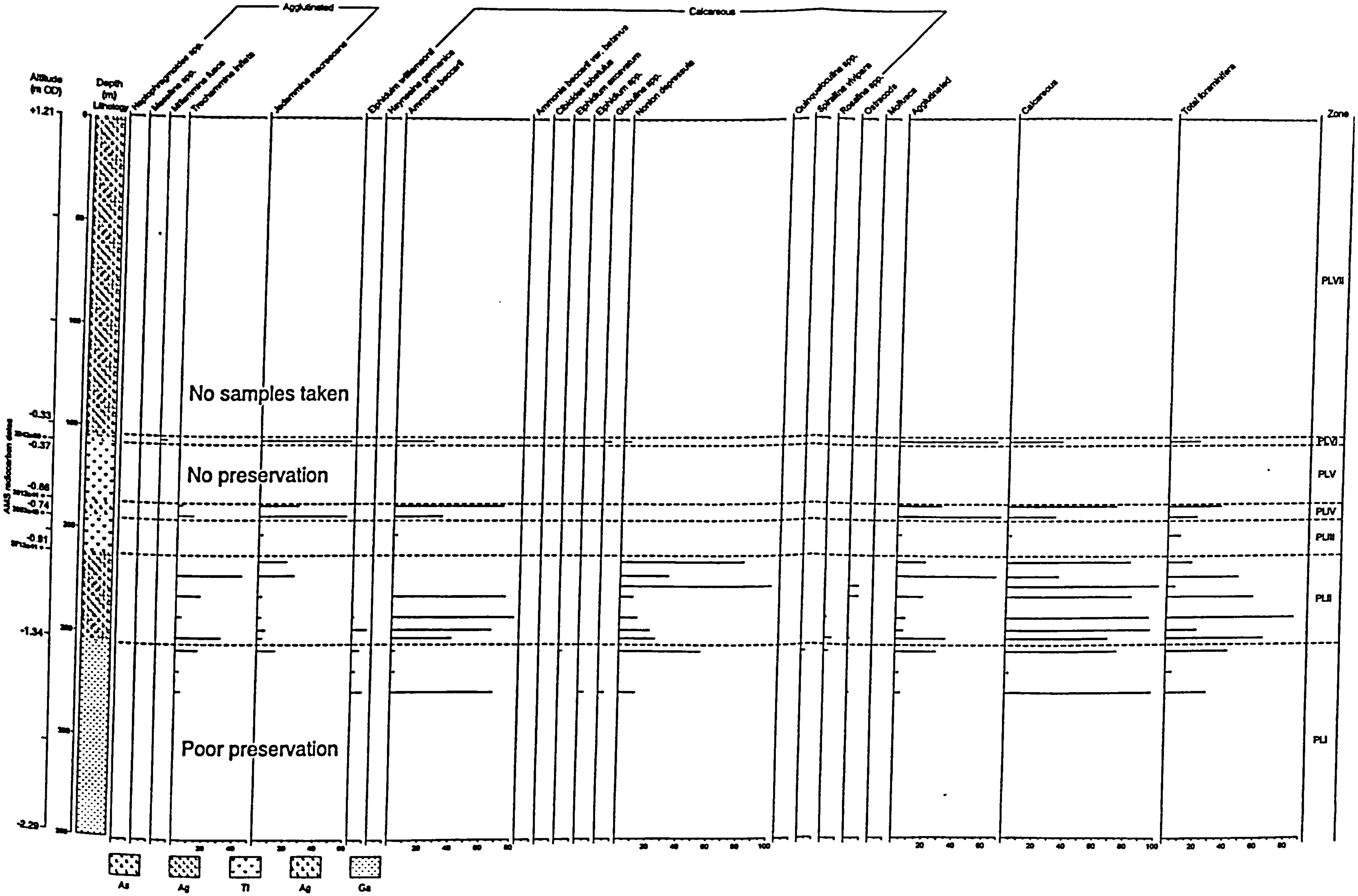


Fig. 4.6 Foraminifera data from the Pevensey Levels, East Sussex
Zones are based upon the stratigraphic boundary divisions and stratigraphic symbols follow the Troels-Smith classification (1955). The data are presented as a percentage of total foraminifera and is divided into agglutinated and calcareous species.

Unit PLI: Sand (-2.29m OD — -1.34m OD)

Although foraminiferal tests were present throughout this unit they were not present in significant quantities. *Ammonia beccarii*, a species commonly found around MHW in low to middle marsh or tidal flat settings, dominated the lower samples accounting for 67% of the total count. However, quantities fell throughout the unit to only 3% in the final sample. Valves of *Trochammina inflata*, a high- to middle-marsh species, started off low and increased throughout the unit. *Elphidium williamsonii* and *Nonion depressulus* were also present but in low quantities.

Unit PLII: Lower silt and clay (-1.34m OD — -0.91m OD)

Once again foraminiferal counts were low. *A. beccarii* and *T. inflata* initially dominated the count, accounting for 60% and 40% respectively. At around 0m OD there was a shift to a dominance by *N. depressulus*, a fully marine species, reaching up to 80% of the total foraminifera. The salt marsh species *Jadammina macrescens* was also present accounting for around 20% of the total foraminifera.

Unit PLIII: Lower peat (-0.91m — -0.74m OD)

Only one sample contained any foraminifera in this unit. At –0.79m OD, in the centre of the unit, *J. macrescens and H. germanica* were recorded albeit in low frequencies, suggesting a low marsh depositional environment.

Unit PLIV: Clay with some silt (-0.74m — -0.66m OD)

This unit contained *J. macrescens* and *A. beccarii* with a small presence of *T. inflata*, indicating deposition under an inter-tidal/brackish.

Unit PLV: Upper peat (-0.66m — -0.37m OD)

No foraminifera were preserved within this unit.

Unit PLVI Transition: Silty peat (-0.37m — -0.33m OD)

It was only possible to take a single sample from this unit since it was only 4cm thick. Some foraminifera were present, but once again in low numbers. *J. macrescens* dominated, accounting for 60% of the total count with *A. beccarii* equalling 25% of the total count. *N. depressulus*, *Globulina* sp. and *M. fusca* were also present, but in much lower quantities.

Unit PLVII: Upper silty clay (-0.33 – +1.21m OD)
No samples were collected.

It is possible to observe several relative sea-level movements from the foraminiferal data. The data suggests that the lowest unit at Pevensey (Unit PLI) was deposited under marine conditions. Species found on sandflat deposits in modern day assemblages including *A. beccarii, T. inflata, E. williamsonii* and *N. depressulus* (Zong & Horton, 1998) were all recorded within this unit. A slight fall in sea-level can be observed after this, shown by the presence of the salt marsh species *J. macrescens* within the lower silty clay unit (Unit PLII). A further fall in sea-level was seen after this, indicated by the low presence of foraminifera in Unit PLIII. A slight return to marine conditions was shown by the return of clay with sand and silt (Unit PLIV), which contained intertidal estuarine foraminiferal species such as *A. beccarii* and *T. inflata*. The peat deposit above this signified another period of reduced marine conditions, confirmed by the lack of foraminifera in Unit PLV. The transitional unit between PLV and PLVI marked a final return to a marine environment, shown by the return of *A. beccarii, J. macrescens, N. depressulus, Globulina sp.* and *Miliammina fusca*, salt marsh dwelling species often found at or around HAT.

Although foraminiferal-based transfer functions have recently been developed (Horton *et al.* 1999, Gehrels, 2000) to reconstruct palaeo-tidal level, the lack of foraminiferal data recorded from the study meant that the transfer function would have add insufficient data to provide a reliable result.

4.5 Summary of palaeoecological data collected from the Pevensey Levels

Each indicator alone provides a tentative conclusion about the pattern of sea-level change. However, when combined, the information becomes much more useful and allows a more complete picture of the sea-level history to be drawn. Fig. 4.7 provides a summary diagram of all the palaeoecological data collected from Pevensey. The diagram has been divided into pollen, diatoms and foraminifera and then sub-divided into the specific habitat types. Table 4.7 provides a summary of the main findings for each stratigraphic unit and suggests a depositional environment.

Unit	Stratigraphy	Biostratigraphy	Depositional Environment
PLVII	Upper silty clay	No pollen preserved Diatoms dominated by *P. sulcata* Low foraminiferal counts	Marine sediment
PLVI	Transition Silty peat	Pollen: woodland dominated Diatoms: *P. sulcata, A. delicatula* Foraminifera: Agglutinated and calcareous *J. macrescens* and *A. beccarii*	Pollen record shows tree pollen blown-in Diatoms and foraminifera suggest low marsh or tidal flats
PLV	Upper Peat	Pollen shows transition from woodland → salt marsh No diatoms or foraminifera preserved	Wetland/woodland → salt marsh → wetland/woodland
PLIV	Silt and clay	Poor pollen preservation throughout Diatoms: *P. sulcata, A. delicatula* Calcareous and agglutinated foraminifera: *A. beccarii, J. macrescens* and *T. inflata*	Diatoms suggest a marine or tidal flat environment Foraminifera suggest an estuary *J. macrescens* suggests tidal marshes
PLIII	Lower Peat	Pollen: Gramineae dominates, with varying proportions of tree pollen present Poor diatom preservation Agglutinated foraminifera: *J. macrescens*	Initially a low marsh environment, increasing in wetness followed by a shift to woodland – dominated by *Alnus* and *Betula*
PLII	Lower silty clay	No pollen preservation Diatoms: *P. sulcata, A. delicatula* Calcareous and agglutinated foraminifera *T. inflata, A. beccarii* and *N. depressulus*	Diatoms suggest marine/tidal flats Foraminifera: *T. inflata* = lagoon – but often washed-in A. *beccarii* =lagoon/ estuary, *N. depressulus* = common Channel species
PLI	Sand silt and clay	No pollen preservation Poor diatom preservation Calcareous foraminifera *A. beccarii, N. depressulus* common to English Channel	Estuarine – intertidal low marsh

Table 4.7 Summary of the palaeoecological data collected from the Pevensey Levels

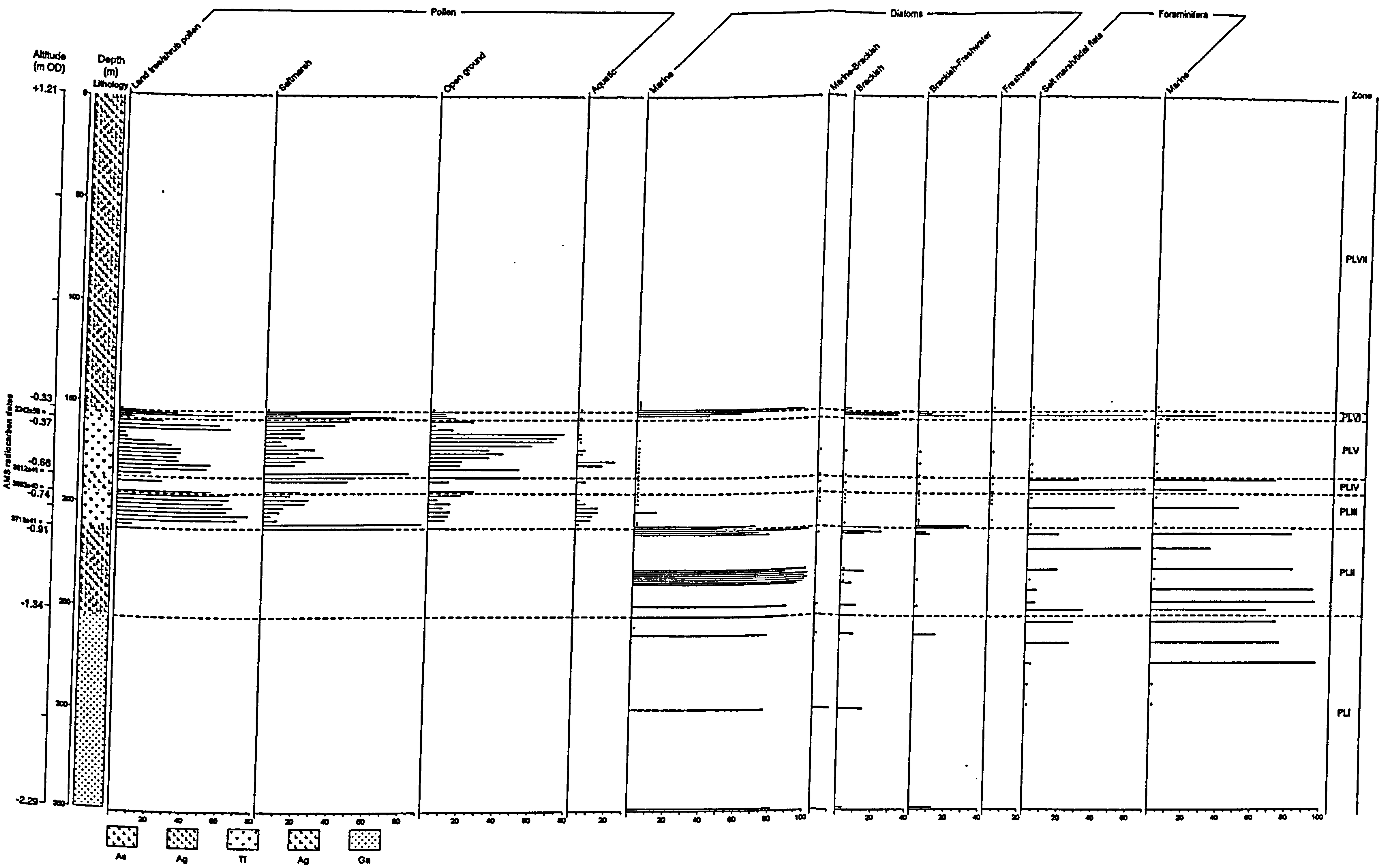


Fig. 4.7 Summary of palaeoecological data from the Pevensey Levels, East Sussex
Zones are based upon the stratigraphic boundary divisions and stratigraphic symbols follow the Troels-Smith classification (1955). The data are divided into pollen, diatoms and foraminifera and each is then subdivided and presented as relative percentage of the indicator.

4.6 AMS Radiocarbon Dating

AMS radiocarbon dates were obtained from six of the cores collected from the Pevensey Levels. Core PL BH2 was selected as the sample core and the dates were obtained from four of the stratigraphic overlaps; the contact between Unit PLII and Unit PLIII, the contact between Unit PLIII and PLIV, the shift from Unit PLIV to Unit V and at the top of the transition between Unit PLV and PLVI. In order to assess the timing of these potential marine regressions and transgressions across the Levels, AMS dates were also obtained from the lowest regressive contact (PL BH-2) and from the lowest transgressive contact (PL BH-4). In addition to these positions, dates were also obtained from the bottom of the peat layer *c.* 0m OD in cores PL BH11, PL BH25 and PL BH-3. This was done in order to determine the timing of peat development across the Levels. Lastly, a date was obtained from the top of the peat layer in unit PL BH25, as it appeared to represent the highest transgressive overlap position. Table 4.7 provides a summary of the AMS radiocarbon results, including calibrated ages.

4.7 Sea-level change on the Pevensey Levels, East Sussex

The following section provides an account of the mid- to late-Holocene relative sea-level change that has taken place at the Pevensey Levels. Fig. 4.8 presents an age-depth plot of the sea-level index points obtained from the Pevensey Levels. All the sea-level index points obtained from Pevensey were assigned a date younger than 4000 years BP. The reference water level for each sea-level index point is mean high water spring tide. The horizontal error bar represents the AMS radiocarbon dating errors (1σ and 2σ). The upward arrows represent marine transgressions and the downward arrows represent marine regressions. Those points with no arrow assigned and shaded grey represent AMS radiocarbon dates that were not assigned an indicative meaning due to lack of palaeoecological data.

The sea-level index points from across the Pevensey Levels appear to fall into two clusters, indicating three phases of coastal change. The first group falls between *c.* 4500 and *c.* 3500 cal. BP and the second group of dates falls between *c.* 3500 and *c.* 2000 cal. BP. The dates in the first group represent regressive phases, except for one of the dates from PL2, the sample core, which revealed a transgressive overlap. All the dates in the second group represent transgressive overlaps, indicating that a relative rise in sea-level probably took place some time after 3500 years BP. These clusters suggest that the pattern of relative sea-level rise may have been complicated by a number of factors.

Stratigraphic position	Core	Lab code	Conventional Radiocarbon Age (years BP +/- 1 σ)	$\delta^{13}C_{PDB}$‰ +/- 0.1	Calibrated years (2 σ)	Altitude of sample (m OD)
Regressive	PL BH2	AA-44079	3713 ± 41	-29.1	4144 - 4027- 3982	-0.91
Transgressive	PL BH2	AA-44081	3663 ± 40	-29.2	4081 - 3935 - 3867	-0.74
Regressive	PL BH2	AA-44080	3612 ± 41	-30.5	3978 - 3901 - 3779	-0.66
Transgressive	PL BH2	AA-44082	2242 ± 59	-28.9	2340 - 2221 - 2116	-0.37
Transgressive	PL BH-4	CAMS-80718	2945 ± 40	-28.8	3206 - 3129 - 2955	-1.64
Regressive	PL BH-3	CAMS-78980	3460 ± 40	-29.5	3825 - 3694 - 3612	-0.81
Regressive	PL BH-2	CAMS-78981	3780 ± 60	-27.9	4240 - 4149 - 3932	-1.58
Regressive	PL BH11	CAMS-78982	3860 ± 50	-27.5	4407 - 4254 - 4093	-0.07
Transgressive	PL BH25	CAMS-78983	2250 ± 60	-30.1	2342 - 2218 - 2118	+0.73
Regressive	PL BH25	CAMS-78984	3720 ± 40	-28.9	4146 - 4025 - 3928	-0.15

Table 4.7 Summary of AMS radiocarbon data obtained from the Pevensey Levels

Interpreting the development of the Pevensey Levels based upon relative sea-level movements alone during this period is therefore not possible. It is apparent that other factors have contributed to the sedimentation patterns observed across Pevensey. When compared with other studies in south east England (Jennings & Smyth, 1987, Long & Innes, 1993) it becomes clear that local coastal processes have complicated the depositional history of the Pevensey Levels.

Phase 1 Prior to c. 4000 ^{14}C years (4500 cal. BP)

The stratigraphic and biostratigraphic data record two periods of marine influence prior to 4000 ^{14}C years. The first period resulted in the deposition of a lower, sandy silty clay deposit (Unit PLI). The presence of the calcareous foraminifera *A. beccarii* and *N. depressulus,* confirmed that this unit was deposited under a marine environment and that it was almost certainly a tidal flat. A period of decreasing water depth followed this, the timing of which could not been determined since no organic matter was present to obtain an AMS radiocarbon date from. A gradual change to a more shallow and calm water depositional environment was shown by the shift from sandy silty clay to blue-grey silty clay (Unit PLII). The calcareous-type foraminifera *A. beccarii* and *N. depressulus* continued to be present. However, *T. inflata* an agglutinated-type foraminifera normally associated with lagoons, but often washed-in, was also recorded. The diatoms indicated that a mudflat environment existed at this time, with *A. delicatula* and the marine species *P. sulcata* dominating the record. The data point to the existence of a calm water environment, possibly a shallow estuary or lagoon, prior to *c.* 4000 years BP.

Phase 2 c.4000 ^{14}C years – c. 3000 ^{14}C years (3500 – 2000 cal. BP)

Phase 2 was marked by the onset of peat deposition across the Pevensey Levels. The earliest peat growth was recorded in PL BH11, where the bottom of the peat (–0.07m OD) was dated to 3860 ± 50 years BP. The deepest regressive contact was found in PLBH-2 at –1.58m OD), dated at 3780 ± 60 years BP. Elsewhere across the Levels, peat initiation has been noted at different altitudes but all recording similar timings. In the sample core (PL BH2) the onset of the lower peat (Unit PLIII) at –0.91m OD, was dated at 3713 ± 41 years BP, but in PL BH-3 the lower regressive overlap at –0.81m OD occurred slightly later at 3460 ± 40 years BP. The variation between the timings of the peat growth can be explained by examining their spatial distribution. PL BH-3 is closest to the present day coast and it is possible that marine conditions prevailed for longer at this site than at the borehole sites further inland (PL BH2), indicating a south east extension of the peat. That is the altitude of the peat would lower in the cores taken from further inland. Since the stratigraphic overlap exhibited a gradual change from silty clay to peat, it would seem likely that this transition to a lower sea-level took place over several hundred years or that sediment was forming in response to both a rising sea-level and the extension of the gravel barrier.

The pollen recorded in the lower peat in PL BH2, revealed that the peat formed initially under decreasing marine conditions, seen by the presence of Gramineae and tree species, then under an increase in marine conditions, shown by the presence of salt marsh taxa. This type of transition has been shown at other sites, shown to be favoured by a slow rate of sea-level rise coupled with the presence of a shingle barrier (Long & Innes, 1993).

A change from peat to a thin silty layer (Unit PLIII to Unit PLIV) can be seen to occur within the second phase and was dated in PL BH2 to 3663 ± 40 at a height of –0.74m OD. Stratigraphic evidence alone would suggest that this change in sediment represented a transgressive overlap. However, the pollen data were too sparse to provide any useful interpretation until the upper stratigraphic contact when Chenopodiaceae pollen appeared, as was the diatom record. The foraminiferal record showed a dominance by *Ammonia beccarii*, usually recorded on low marsh deposits several metres below MHWST (Haslett *et al.*, 1997) and *Jadammina macrescens*, a middle marsh deposit often used as an important salt marsh indicator. These results implied that the area was still a salt marsh at the time of deposition, although the rate of sedimentation may have changed.

The abrupt nature of the lower stratigraphic contact would initially suggest that a fairly sudden marine incursion had taken place. The lower contact was dated at 3663 ± 40 yrs BP and the upper contact at 3612 ± 41, which produces a sedimentation rate of 6mm per year, indicating rapid sedimentation at this time. If the 2σ dates are used (3868 and 3779) then a sedimentation rate of 7mm per year can be determined. Although these points could represent a shift from middle marsh to lower marsh, it is more likely that this thin silty unit, which was recorded in some but not all of the boreholes taken across the Levels, represents a salt marsh tidal channel deposit and not a rise in relative sea-level. The presence of the foraminifera *J. macrescens*, a species found just below MHWST (Haslett *et al.* 1997), supports this theory, as it is unlikely that this species would have been present had a full marine incursion taken place.

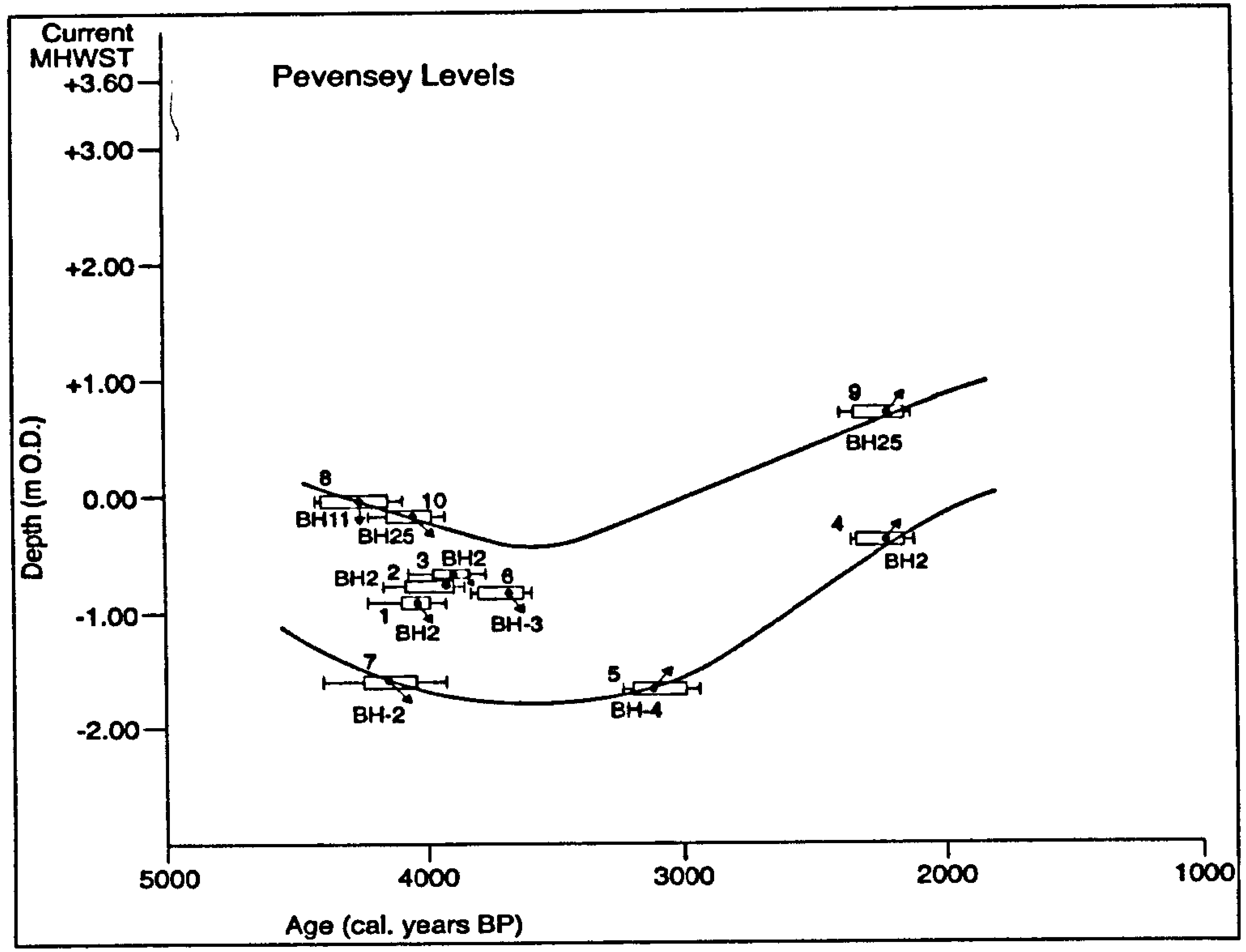


Fig. 4.8 Age-depth plot of sea-level index points from the Pevensey Levels, East Sussex

The horizontal error bar represents the AMS radiocarbon dating errors (1σ and 2σ). The arrows indicate whether a marine transgression or regression took place. Shaded boxes indicated that no indicative meaning could be assigned. A sea-level band has been added to assist in showing the minimum and maximum index points.

Several thin inorganic layers have also been recorded across the Willingdon Levels near Eastbourne (Jennings & Smyth, 1982), the origin of which was attributed to migration of river channels or periodic barrier breaching; they were not thought to be the result of a marine transgression. The intercalated silt layer could support the theory of back-barrier tidal channel migration as proposed by Long & Innes (1993) for similar sediments recorded on Romney Marsh. The multi-palaeo results (Fig. 4.7) presented little evidence for a change in the depositional environment. The pollen and foraminiferal records were dominated by salt marsh-types, suggesting the surrounding vegetation and habitat had little time to respond to the changing conditions. It is therefore, possible that this deposit could represent a flood or storm deposit. The silty nature of the sediment implies a marine depositional environment and the fact that the deposit is so thin implies a fairly rapid rate of deposition. Although the rapid sedimentation and nature of the sediment could support the theory of a rapid flooding event, without further evidence, such as a distinct increase in the sediment particle size, it seems more likely that the unit represents a tidal channel deposit.

The timing of the upper peat development also agrees with the theory of a tidal channel deposit, suggesting that in fact only a single peat unit was deposited across the Pevensey Levels. In PL BH2 an age of 3612 ± 41 years BP at a height of –0.66m OD was obtained and in PL BH25, further inland, a date of 3720 ± 40 years BP at a height of –0.15m OD was recorded. As it can be seen in Fig. 4.7 and from the description above, these do not differ greatly from the dates obtained from the lower regressive overlap.

On the basis of the biostratigraphic evidence and the radiocarbon dates, the two dates obtained from BH2; 3663±40 yrs BP at –0.74m OD and 3612±41 yrs BP at –0.66m OD have been rejected as sea-level index points since they do not represent deposition at or around MHWST. These two points have therefore been excluded from future discussion and are not included in any of the cross-channel or geophysical modelling comparisons.

Phase 3 Post 3000 ^{14}C years (post 2000 cal. BP)

The final phase of coastal evolution at Pevensey began around 3000 ^{14}C years BP. The earliest return to fully marine conditions was recorded in PL BH-4, close to the present day coastline. This transgressive overlap yielded a date of 2945 ± 40 years BP (3129 cal. BP) at a height of –1.64m OD. The transition from peat to the upper silty clay was also dated at 2242 ±

59 years BP at a height of –0.37m OD in PL BH2 and 2250 ± 60 years BP at a height of +0.73m OD in PL BH25, further inland. This marine incursion is supported by the presence of the marine species *Acnanthes delicatula* and *Paralia sulcata* in the diatom record and *Ammonia beccarii* in the foraminiferal record.

Summary

The above three-phase model appears to explain a complex pattern of both relative sea-level change and the existence of a coastal barrier. The three phases agree closely with interpretation from other coastal sites that are thought to show the presence of a coastal barrier (Jennings & Smyth, 1990; Long & Innes, 1995). The onset of peat development across the Levels *c.* 3700 years BP (4027 cal. BP) occurred in response to a slowing rate of sea-level change and the initiation of a barrier allowing peat forming communities to develop slowly in its lee. Peat continued to extend across the Levels, with the pollen record exhibiting clear shifts from wetland to woodland environments. The final phase marks the return to marine conditions, resulting from destabilisation of the coastal barrier and a regional rise in sea-level.

4.8 Estimate of sediment compaction

As previously discussed in Chapter Three, an attempt has been made to estimate the amount of sediment compaction that has taken place on those cores from which sea-level index points have been obtained. It must be stated that this is a simple estimate made using an exploratory model (Allen, 1999), and not an attempt to accurately devise a decompaction model. On each of the cores that contain sea-level index points, Allen's equation (refer to equation 3.1 Chapter Three) has been employed to estimate by how much each point has been lowered as a result of sediment autocompaction. The detailed results of the calculation are contained in Appendix IV. A summary of the results is however, presented in Table 4.8. In order to ensure that Allen's equation was appropriate to the study site, bulk densities were obtained from the sample core at Pevensey (by obtaining the difference between the dry weight and the original wet weight of the sediment) and compared to the bulk densities used by Allen (1999). The result for silt fell at the lower end of Allen's range, with a bulk density of 1.797t m^{-3}, where Allen's range was 1.70 – 2.60t m^{-3}. The result for peat also fell within the range, with a bulk density of 0.362t m^{-3}, where the range was 0.25 – 1.14t m^{-3}, suggesting that compaction would be relatively low since the bulk density fell towards the bottom end of the bulk density range.

Firstly, it must be noted that SLIP2 and SLIP3 from the Pevensey Levels sample core have been included in the table. These points have previously been rejected as valid sea-level index points, as discussed above. However, it was useful to include these in the results to highlight the differences in the compaction rates seen between different sediments and between different boreholes. The results from SLIP2 and SLIP3 will not be included in any further analysis.

Sea-level index point	Original depth (m OD)	Estimated decompacted depth (m OD)	Estimate of compaction (m)	Percentage compaction (%)
Sample Core SLIP1 Lower regressive overlap	-1.187	-1.187	0	0
Sample Core SLIP2 Lower transgressive overlap	-0.737	-0.277	0.46	63
Sample Core SLIP3 Upper regressive overlap	-0.707	-0.07	0.007	1
Sample Core SLIP4 Upper transgressive overlap	-0.407	-0.158	0.249	61
PL BH –4 Transgressive overlap	-1.591	-1.195	0.396	24
PL BH –3 Regressive overlap	-0.814	-0.814	0	0
PL BH –2 Regressive overlap	-1.581	-1.581	0	0
PL BH 11 Regressive overlap	-0.065	-0.065	0	0
PL BH 25 Regressive overlap	-0.152	-0.152	0	0
PL BH25 Transgressive overlap	0.728	1.213	0.485	66

Table 4.8 Estimations of sediment compaction on the sea-level index points obtained from the Pevensey Levels, using Allen's (1999) exploratory equation of autocompaction

The estimates of sediment compaction clearly show that all the cores obtained from the Pevensey Levels have been subjected to considerable post-depositional compaction. Although for the purposes of this research, compaction has only been estimated on those cores from which sea-level index points were obtained. Most notably are those points taken from the top of peat units, representing transgressive overlaps, which revealed that compaction of up to 63% can occur. Greensmith & Tucker (1980) suggested that peat could compact to up to 10% of their original thickness, highlighting the importance of estimating compaction.

The results presented in Table 4.8 also highlight one of the main limitations of employing Allen's (1999) equation to the study sites. At this time, with the current available data and the components of the compaction equation, the sea-level index points taken from the lowest regressive overlaps were treated as basal peats. Since no basal peat data was available from Pevensey, there was no reference point available. Thus, the lowest peat had to be assumed to be resting on a non-compactable surface, in order for the equation to perform successfully. Therefore, for many of the sea-level index points obtained from the bottom of peat units, it has not been possible to apply an estimate of compaction since they had to be assumed to be resting on a incompressible surface. If the BGS data had been quantitatively reliable then it may have been possible to provide a more accurate estimate of compaction, although with the current decompaction models available, it would still have only been an estimate.

Once the estimates of compaction had been made, the results were plotted against the original age-depth data (see Fig. 4.9). The de-compacted estimates made little overall difference to the age-depth plot. Three distinct groups were still visible, suggesting that the pattern of change identified is closely linked to the development of a coastal barrier, as previously discussed. It had been hoped that the differences between the altitudes of the regressive overlaps in Phase 2 would have been explained by differential compaction. However, no reliable estimates could be obtained.

A reliable estimate of sediment compaction could not be obtained from Pevensey using the exiting data and compaction models. In order for compaction to be quantitatively determined basal peats would need to be sampled from Pevensey, in order to provide a reference point that is unaffected by compaction and Allen's (1999) model would require further empirical data to incorporated, including compressibility terms for clay and sand.

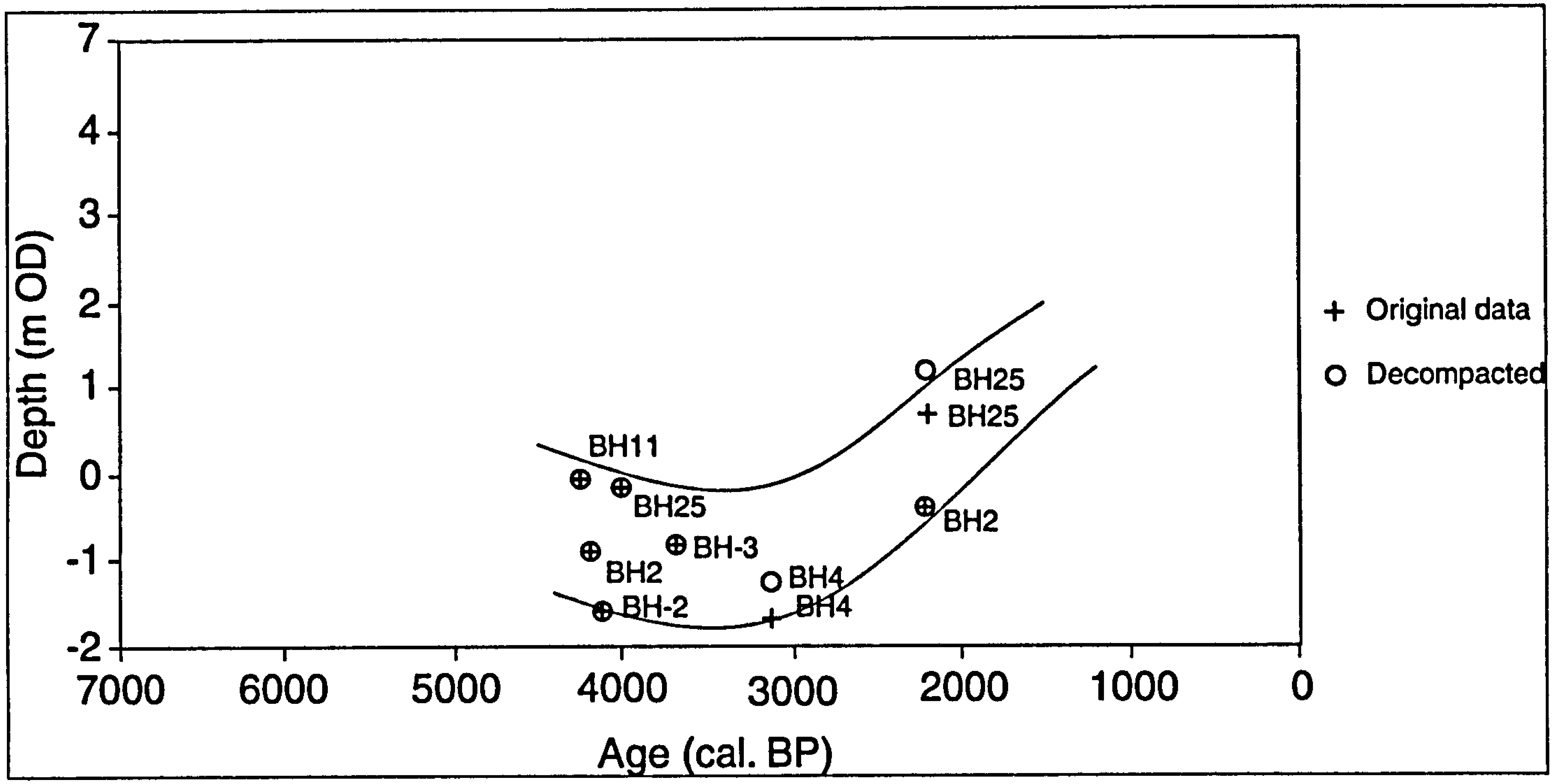


Fig. 4.9 Age-depth plot of observed and estimated decompacted sea-level index points from the Pevensey Levels, East Sussex

4.9 Discussion of recording sea-level signals in barrier-influenced coastlines

Before a comparison between the results from the Pevensey Levels and other sites in south east England can be attempted, it is important to discuss the implications of obtaining sea-level signals from back-barrier environments. Coastal barriers exert a significant influence upon the pattern of coastal sedimentation (Jennings & Smyth, 1982, 1985; Long & Innes, 1993). The presence of a coastal barrier will result in a greater number of stratigraphic units being recorded, as the barrier experiences changes in its configuration. Changes in the size of the barrier inlet, will produce what can appear to be a greater number of changes in marine activity. An increase in the size of the inlet, will allow marine inundation to take place and thus a sediment recorded in a back-barrier environment which appears to be marine in origin can not be assumed to have been deposited resulting from a rise in sea-level. However, it is also possible that the increase in the size of the inlet was a direct result of an increase in storm activity or a rise in sea-level, causing the barrier to be breached and begin to break down. A reduction in the size of the barrier inlet is most likely to result from an increase in the supply of sediment from along the coastline, resulting from increased coastal erosion. This would allow stabilisation of the barrier and the formation of peat deposits in its shadow.

The relationship between sea-level and barrier-dominated coastlines is therefore intrinsically linked. The sediments that are able to develop relate directly to a number of processes that are operating on the coast. An advantage of studying back-barrier environments is that a great number of stratigraphic changes can usually be recorded, offering a greater number of potential sea-level index points. This can provide a much more complete pattern of the rate of sea-level rise.

4.10 Comparison with other sites in south east England

The complex pattern of barrier dynamics coupled with changes in relative sea-level which have been dominant in the development of the Pevensey Levels agrees closely with the findings of other studies in East Sussex and Kent. Having already established that the sediments at Langney Point, Eastbourne formed in response to the development of a gravel barrier (Jennings & Smyth, 1982, 1985, 1987), Jennings & Smyth (1990a) produced a five-stage model of coastal evolution during the Holocene. The pattern of sedimentation recorded on the Pevensey Levels agrees well with their Stage 2 (10 000 to 5000 years BP), a period of rising sea-levels and the presence of a series of tidal channels. Similarities to Stage 3 (5000 – 300 years BP), which was a period of stable sea-level coupled with the movement of gravel onshore leading to the development of a gravel barrier, can also be observed, although at Pevensey there is less evidence of a gravel component in the sediments. Despite these similarities, the timing of barrier destabilisation does not correspond. This appears to have occurred much earlier at Pevensey (*c.* 3000 years BP) than at Langney Point (post 300 years BP). A further problem remains in identifying the source of the sediment responsible for the development of the barrier. Jennings & Smyth (1982, 1990) proposed two possible sources for the sediment that supplied the gravel barrier, including cliff retreat and the offshore zone, concluding that the offshore zone was the most likely source. Offshore drillings would have been required in order to determine the source of sediment supply at Pevensey, unfortunately this was beyond the scope of this research.

The most effective method of observing any similarities and differences between regions is to plot the sea-level index points obtained from the Pevensey Levels against those obtained from other regions of south east England. In order to allow direct comparisons, only sites where index points were obtained from intercalated peat deposits were selected and decompacted estimates are not included, as many of the results do not include estimates of compaction. It must be stressed that this is not an attempt to produce a regional sea-level curve. It is simply being used as a method of comparing sites. Sea-level index points obtained from Essex (Greensmith & Tucker, 1973, 1980) were obtained from the chenier deposits and not intercalated clays, silts and peats, have therefore not been included. The sea-level index points obtained from the Thames Estuary (Devoy, 1979) have also not been included in this comparison due to the severe differential subsidence that was recorded between the mid and inner estuary. Fig. 4.10 provides an age-depth plot of sea-level index points obtained from Romney Marsh (Long & Innes, 1993), East Sussex (Jennings & Smyth, 1987; Smyth & Jennings, 1988), the East Kent Fens (Long, 1991, 1992) and the Pevensey Levels, East Sussex. The graph is an adaptation of the plot published by Long & Innes (1993 p.232 Fig. 5c).

It can be seen that a general curvilinear rise in sea-level has taken place throughout the Holocene period. The curve shows that this rise in relative sea-level was initially fairly rapid (approximately 23m over 4000 years) but then slowed down at around 5000 years BP, a pattern observed across most of north west Europe (refer to Chapter 2.2). The period of most interest for this study is the latter part of the Holocene, since the index points obtained here all plot within the last 4000 ^{14}C years BP.

The age-depth plot revealed that both Eastbourne and Romney Marsh also exhibit three clusters of sea-level index points. The overall pattern of sea-level change seems to fit well with that observed at Pevensey, however the timings do not correspond. The first cluster detected in Eastbourne and Romney occurred between 6000-5000 years BP (evidence of a rapidly rising sea-level), a period for which no dates were obtained from the Pevensey Levels. The second cluster observed at Romney and Langney Point, East Sussex occurred post-4000 years BP. This corresponds well with the first cluster of index points obtained from Pevensey. The third cluster can be observed at all the sites, showing index points grouping at around 2000 years BP.

The East Kent Fens however, shows a quite different pattern and rate of sea-level change. Although a curvilinear rise has been observed, all the dates plot well below those obtained from Eastbourne, Romney Marsh and the Pevensey Levels. Long (1991) concluded that no differential subsidence had taken place and that no local factors, such as barrier development, had influenced the sea-level record in the East Kent Fens. This highlights the difficulties posed when attempting to draw comparisons between sites where local effects exert a significant control on the change in sea-level, once again stressing the need for sea-level reconstructions to be attempted at the single-estuary scale. If single sites are used, the problem of including data from estuaries where a variety of different local controls are exerted upon the pattern of coastal development is avoided, which in turn will not affect the sea-level signal detected at these sites.

The comparison between the sites along the south east coast also shows that the sea-level index points obtained from the Pevensey Levels plot much higher than those from elsewhere. This could be the result of differences local factors, such as differential subsidence, since the estimates of compaction provided would not significantly alter the altitudes of the index points.

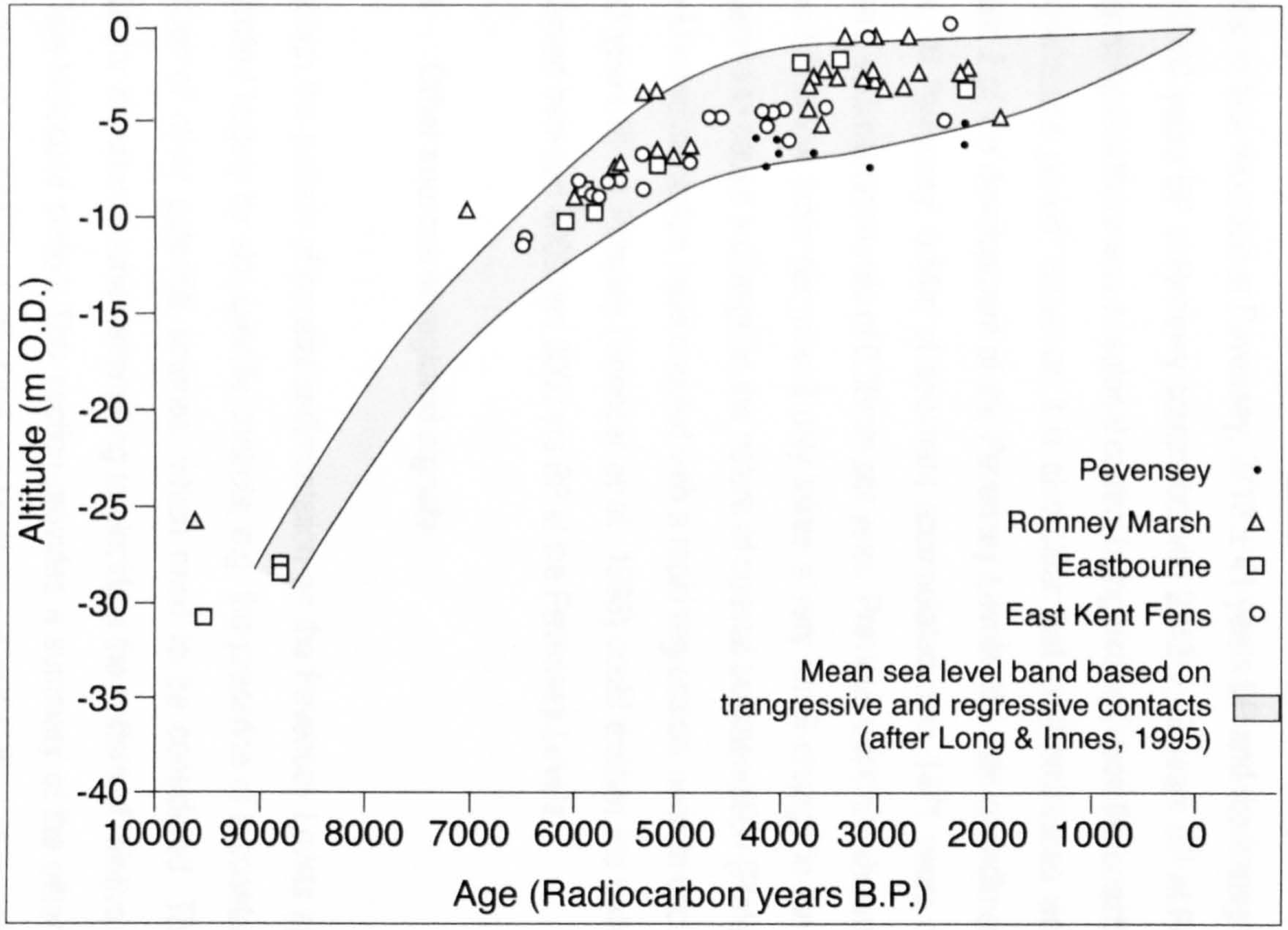


Fig. 4.10 Age-altitude plot for south east England based upon data from Romney Marsh, Kent (Long & Innes, 1993), East Sussex (Jennings & Smyth, 1987, Smyth & Jennings, 1988), East Kent Fens (Long, 1991, 1992) and the Pevensey Levels, East Sussex.

Adapted from Long & Innes (1993)

The timing and overall pattern of mid- to late-Holocene sedimentation at Pevensey, shows many similarities to that recorded at Romney Marsh. Firstly, the stratigraphic record exhibits many similarities. If the thin silty layer at Pevensey (Unit PLIV) is assumed to represent a tidal channel, as described by Long & Innes (1995), shown by thin lenses of inorganic material with a maximum thickness of 0.10m, then the stratigraphic record is directly comparable to that of Romney. Secondly, the timing of the regressive overlap, *c.* 4000 years BP at Romney is very similar to that recorded at Pevensey, 3713 ± 41 years BP and the transgressive overlap dated at *c.*2000 years BP at Romney compared with 2242 ± 59 years BP at Pevensey, once again suggesting that there was a regional control being exerted upon the coastline during the mid- to late-Holocene period. However, it is also clear that local processes were important. During Phase 2 of the development of the Pevensey Levels, the rate of sedimentation was probably slow. At Pevensey, 0.54m of sediment accumulated over 1471 years during phase 2. This gives a sedimentation rate of 0.36mm per year. Previous work has shown that if sedimentation rates fall below 1mm per year it only takes a very small change in the morphosedimentary dynamics to cause a change in the nature of coastal sedimentation (Plater & Shennan, 1992). The low sedimentation rates coupled with a rapid regression, seen to occur between 4500 and 3000 years BP at Romney (Spencer *et al.,* 1998) could explain the pattern of sedimentation observed between 4000 and 3000 yrs BP at the Pevensey Levels.

4.11 Other sources of regional signals

Although the pattern of coastal sedimentation on the Pevensey Levels appears to have been controlled largely by site-specific controls, e.g. the presence of a coastal barrier, there are a number of other potential sources, which need to be considered. These sources are of particular importance when attempting to elucidate the pattern of relative sea-level change for the late-Holocene period. This section provides a summary of the other sources of regional signals that are known to affect the sea-level record and pattern of coastal evolution. Although this is discussed at the end of the Pevensey Levels discussion chapter, the sources cited are relevant to all the study sites (refer to Chapter Five, Six and Seven also). It will become apparent that most of the sites studied as part of this research have been dominated by site-specific controls. However, the effects of regional sources must not be excluded from the interpretation process and thus it is important to discuss them at this stage.

The last 3000 years (often referred to as the Sub-Atlantic) has witnessed a clear shift in climate. Broadly the climate can be described as being cool and wet until 2000 years BP, which in the south eastern region of England allowed peat accumulation. From around 2000 BP there has been a shift to warmer climate, and more importantly and increase in human activity (Roberts, 1989).

It is possible to divide the main sources of these regional signals into four groups: climate change (including changing river dynamics), changing sediment fluxes, tidal changes and human impact. Of course these are all inter-related, "the degree of connectivity between river, estuarine and coastal transport systems as well as the spatial and temporal variations in fluvial sediment storage, are the key controls of long-term land-ocean sediment fluxes" (Macklin *et al.*, 2000 p. 87), but for the purpose of this discussion will be separated.

Changes in climate, such as an increase in wetness resulting from increased precipitation can have a number of important effects on the coastal environment. For example an increase in wetness and fall in transpiration will result in increased surface runoff (Waller, 1993). This can alter the dynamics of the river regime and result in increased flooding, both magnitude and frequency. Long *et al.*, (1996) noted that increased periods of wetness tended to correspond with a rise in sea-level and shoreline retreat. A rise in the water table and an increase in flooding will also increase surface runoff. A second effect of increased surface runoff is that the amount of soil erosion taking place, thus altering the amount of terrigenous sediment available to the area. Changes in river dynamics, resulting from increased wetness will therefore exert a significant control of the pattern of coastal development. Rivers will deposit their sediment, building up the land and pushing the shoreline seaward (Waller, 1993). Several examples of climatically-induced changes in sea-level have been published. On the Severn Estuary, Allen & Rae (1987) suggested that the frequency of westerly and south westerly winds were one of number of possible causes of relative sea-level rise. Other possibilities included offshore shoal movements and changing sediment influx, which will be discussed later in this section. In the Netherlands storm surges have been associated with climatic deterioration, which is thought to have been the driving force in barrier breaching (Bell & Walker, 1992). In Sussex, coarser sediments have also been recorded, thought to be associated with increased storm activity in the 13th Century (Waller, 1994).

Changes in the sediment flux will exert a significant control of the pattern of coastal evolution and thus the sea-level signal recorded on estuarine sites. Enhanced sediment supply can be attributed to changes in climate change and this changing river dynamics, as previously discussed, or increased human activity (Plater *et al.*, 2000), which will be discussed later. This increase in terrestrial sediment will result in a change from organic to minerogenic deposition (Plater *et al.*, 2000). Thus, when trying to interpret coastal sedimentation and relative sea-level change, it is often useful to know the origin of the minerogenic sediment. This can often be done using PSA and geochemistry, as discussed in Chapter Two.

Changes in the tidal regime has also been identified a major factor in the signal of sea-level recorded at coastal estuarine sites. Changes in the tidal dynamics will control the amount of sediment supplied to a site and will affect the pattern of coastal sedimentation. Tidal asymmetry has been found to determine the balance between sediment accretion and erosion (Metcalfe, 2000). However, this is still an area of research that is yet to be fully explained. Several studies have attempted to produce a model of tidal range for the Holocene (Austin, 1991 and Hinton, 1992). However, the most comprehensive study was carried out by Shennan *et al.*, (2000) who produced a model of tidal change using 26 tidal harmonics. The aim of the study was to predict tides for certain types of past coastal bathymetry and configuration. The model predicted that there had been an increase in tidal range during the Holocene for most sites in north west Europe. This included an increase in high tide level. Therefore, it can be seen that change in the tidal range will almost certainly affect the pattern of sea-level recorded at specific site. Elucidating the changes in tidal range should become easier as more data become available from tide gauge records.

The final regional source, and possibly the most important for the last 2000 years, is that of human impact upon the land. The late-Holocene period has been affected by the exploitation of human activity, in particular in the coastal zone, an area which is attractive to settlers due to their low-lying relief and the resources that they offer (Waller, 1993). One of the biggest impacts of human activity has been forest clearance. This method of management can result in an increase if surface runoff, leading to an increase in stream flow and a rise in eutrophication (Waller, 1994). Removal of trees will also increase the amount of sediment influx into an area (Plater *et al.*, 2000), causing changes from organic to minerogenic sedimentation. Forest clearance was used intensively by the late Neolthic / early Bronze Age settlers in south east England, and the clearance involved preferential exploitation of particular tree species, e.g.

Tilia (Waller, 1993). Evidence for clearance is good in most pollen diagrams from the late-Holocene period. Forest disturbance is also known to increase waterlogging (Waller, 1994) which at many coastal sites could explain the presence of *Alnus* pollen in the pollen record.

Impacts of grazing and burning, and other agricultural practices, upon the landscape during the late-Holocene are well known (Bell & Walker, 1992), however it is thought that these activities affected lowland coastal sites less than other sites, and thus will not have affected the pattern of coastal sedimentation and relative sea-level change.

Human impact, other than forest clearance, is often difficult to detect, unless archaeological remains are recovered (Bell & Walker, 1992). However, more recently attempts have been made to trace the impact of human activity using geochemical analysis (refer to Chapter Two for methodology). The beginnings of industrial activities can be shown by the changes in metal contamination through the sediment. In the Tees Estuary research revealed that an enhanced sediment supply had resulted initially from land clearance and secondly from mining and industrial expansion (Plater *et al.*, 2000). This type of activity is probably less likely to be recorded on the coastal sites of south east England, where activities such as salt workings are more evident (Dulley, 1966). Work in the Tees Estuary (Plater *et al.*, 2000) also concluded that human activity resulted in increased soil erosion, mainly through forest clearance, and that this was particularly evident between 2500 and 3500 yrs. BP.

The above discussion highlights the main controls that can be identified in the coastal zone in particularly in the context of the late-Holocene. It is crucial to attempt to decipher the potential regional and local signals when trying to monitor sea-level change during the Holocene. It can be seen that all the processes described above are intrinsically linked, and it is not possible to discuss one without identifying a change in another. It can also be seen that by studying the regional signals, the local effects can often be detected.

4.12 Conclusion

A three-phase model of sea-level change and coastal evolution explains the mid- to late-Holocene development of the Pevensey Levels. The first phase was characterised by a rapidly rising sea level, with past water level at or around MTL. Peat deposits were then laid down under a period of falling sea-level coupled with the extension of a coastal barrier, resulting in a partially closed estuary. Barrier stabilisation must have taken place between *c.* 4000 and 3000 cal BP, allowing colonization by freshwater and terrestrial species to take place. This was confirmed by the presence of diatoms that favoured tidal depths above MHWST. The final phase was characterised by a period of barrier de-stabilisation, probably resulting from a rise in relative sea-level.

A reliable estimate of sediment compaction could not be made using the available data and autocompaction models. The study recommends that basal peats are obtained from Pevensey in order to provide data that has not been subject to compaction and secondly recommends that the compaction model presented by Allen (1999) is developed further to include empirically derived compressibility terms for clay and sand.

The pattern of mid- to late-Holocene development corresponds well with that recorded at other barrier-dominated coastlines in south east England, namely Romney Marsh and Eastbourne (Long & Innes, 1993, 1995; Spencer *et al.* 1998 and Jennings & Smyth, 1987, 1988), which also exhibit a period of rapidly rising sea-level prior to 4000 years BP, followed by a rapid coastal regression between 4500 - 3000 years BP.

It can clearly be seen from the above discussion that the pattern of coastal evolution is controlled not only by regional processes, such as a rising sea-level, but also by local factors, such as changes in the coastal geomorphology and the tidal regime. Although regional patterns of sea-level change can be detected, for example, the similarities between Romney Marsh and the Pevensey Levels (refer to Chapter Seven for further discussion), the study revealed a significant difference in the altitudes of the sea-level changes. This highlights the need to carry out sea-level studies on single estuaries (Tooley, 1978; Shennan, 1989; Lambeck, 1997) and to not group sea-level curves from different estuaries into a single regional curve as has been shown by the research undertaken on the Pevensey Levels.

Chapter Five Results from the Canche Estuary, N. France

The following chapter provides the results from the Canche Estuary, N. France. The chapter has been divided into six sections, providing the results of the stratigraphic survey and biostratigraphic analyses. A sea-level curve for the Canche estuary is presented along with a comparison between the findings at other sites in northern France.

5.1 Stratigraphic data collected at the Canche Estuary, Northern France

Pre-existing borehole data

Due to the limited number of studies undertaken at the Canche Estuary, pre-existing borehole data was sparse. The Bureau de Recherches Géologiques et Minières (BRGM), the French geological research centre, had performed six borehole drillings in the area, near Villiers (refer to map in Chapter Three Fig. 3.3 and see Table 5.1 below).

The boreholes revealed the presence of alternating sand and silt layers, termed alluvium by the BRGM. Only a single borehole contained organic deposits (Borehole No. 00167X0114/F1). Two peat layers were recorded, a basal peat at 16.7 – 18.6m depth, described as a brown-black peat with wood pieces, which rested on a layer of coarse sand and flints. A clay and sand unit, followed by a sand, clay and peat unit overlay the lowest peat unit. Above this, an upper peat unit was recorded, simply described as brown-black peat at 4.5 – 5.1m depth, which when transformed is approximately 0m NGF.

Also recorded in core 00167X0114/F1 at Villiers, was a stiff white-yellow clay at 2.25 – 4.5m depth. No explanation was provided for the origin of this unit. However, it is possible it could represent a solifluction deposit, or may even be a palaeolimnological deposit. A similar unit was recorded in the Somme Estuary, thought to be a solifluction deposit, but no such deposits were recovered elsewhere across the Canche Estuary.

The basal peat offered the potential to determine the rate of sediment compaction that had taken place and would provide information about the early-Holocene pattern of sea-level change. If the upper intercalated peat unit represented an estuary-wide deposit at around 0m NGF, comparison with other sites in north west Europe would almost certainly indicate a channel-wide signal of sea-level change.

The lowest layers in each borehole were dominated by sand, above which was a grey-blue sand deposit, again indicating the potential for cross-channel comparisons to be made. The uppermost layers indicated a shift to more silty deposits, but with a sand presence persisting, indicating a strong marine influence throughout the late Holocene. Unfortunately, there are several limitations associated with the data. Firstly, depths were only given as depth below the surface and no reference datum was provided, making it difficult to draw comparisons with other borehole data. Secondly, most sediment descriptions were broadly termed alluvium; in which BRGM include silt and sand sediments. Since no explanatory notes accompanied the borehole data, the origin of the term alluvium could not be ascertained. Thus, the BRGM descriptions of the boreholes were too broad for the purposes of a sea-level reconstruction and accurate depths relative to NGF are not known. In order to determine the pattern of stratigraphy at the Canche further examination of the sediments was required.

Stratigraphic survey of the Canche Estuary

The stratigraphic survey was undertaken in a transect parallel to the coastline at Villiers, south of Étaples (see Fig. 5.1). The position of the boreholes may be seen in Fig. 3.3 in Chapter Three. Upon first examination it can be seen that there is a distinct difference between the boreholes taken closest to the River Canche and those taken further inland. Boreholes CA1, CA2 and CA5 did not reveal any buried peat layers and contained mainly sand interspersed with silt, and occasional visible mollusc remains. However, these sand units were impossible to penetrate by hand or piston corer and it may be that lower organic units existed.

Further from the current river channel, the stratigraphy of the estuary changed considerably. Boreholes CA8 and CA6 revealed a similar pattern of deposits to each other. The lowest unit consisted mainly of sand with some silt present. In borehole CA8 a thin silt deposit followed. An organic layer overlay the sand and silt, but only in CA8 can it be described as being a true peat deposit; in core CA6 it was a sandy detritus. Sand and silt dominated all the units above the organic layer with no further organic presence.

Borehole No.	Depth	Description
00163X0071/P2	0 - 0.2	Topsoil
	0.2 - 0.5	Alluvium: Light brown silt
	0.5 - 2.2	Alluvium: Silt and Sand, Light brown
	2.2 - 3.6	Alluvium: Coarse sand, Grey-Brown
	3.6 - 6	Alluvium: Sand, Grey-Blue
		Alluvium: Sand
00163X0073/P3	0 - 0.2	Topsoil
	0.2 - 0.6	Alluvium: Silt, Sand, Light brown
	0.6 – 1.0	Alluvium: Sand, Silty, Grey-White
	1.0 - 2.25	Alluvium: Sand, Grey- Blue
	2.25 – 6.00	Alluvium: Sand, Grey-Blue Shells
		Alluvium: Sand
00163X0074/P4	0 - 0.2	Topsoil
	0.2 – 2.0	Alluvium: Silt, Sand, Light brown
	2.0 - 2.3	Alluvium: Mix of Sandy Silt Light Brown/Sand, Grey-White
	2.3 – 2.5	Alluvium: Sand, Brown-Grey
	2.5 – 6	Alluvium: Sand, Grey Blue
		Alluvium: Sand
00163X0075/P5	0 - 0.2	Topsoil
	0.2 - 0.5	Alluvium: Silt, Sand, Light brown
	0.5 - 1.7	Alluvium: Sandy silt, Grey
	1.7 - 2.2	Alluvium: Sand, Brown-Grey
	2.2 - 2.5	Alluvium: Coarse sand, Grey-Blue
	2.5 - 6	Alluvium: Grey-blue sand
		Alluvium: Sand
00167X0065/T5	0 - 0.3	Topsoil
	0.3 - 3	Alluvium: Sand, Fine clay, Grey-Green
		Alluvium: Sand
00167X0114/F1	0 - 0.25	Fine Light Brown Silty Sand
	0.25 - 0.45	Polder clay, Grey-Brown
	0.45 - 2.2	Fine clayey sand, Light grey-blue
	2.25 - 4.5	Stiff clay, white-yellow
	4.5 - 5.1	Peat Brown-black
	5.1 - 6.6	Fine sand, grey clay, peat, calcareous sand. Grey-white /shell fragments
	6.6 - 7.2	Fine clayey sand, brown
	7.2 - 16.7	Fine clayey sand, Brown with shells and shell fragments
		Peat contact
	16.7 - 18.6	Peat Brown with Brown-Black with wood pieces
	18.6 - 21.2	Coarse sand with flints (dark blue)

Table 5.1 Summary of BRGM borehole data from the Canche

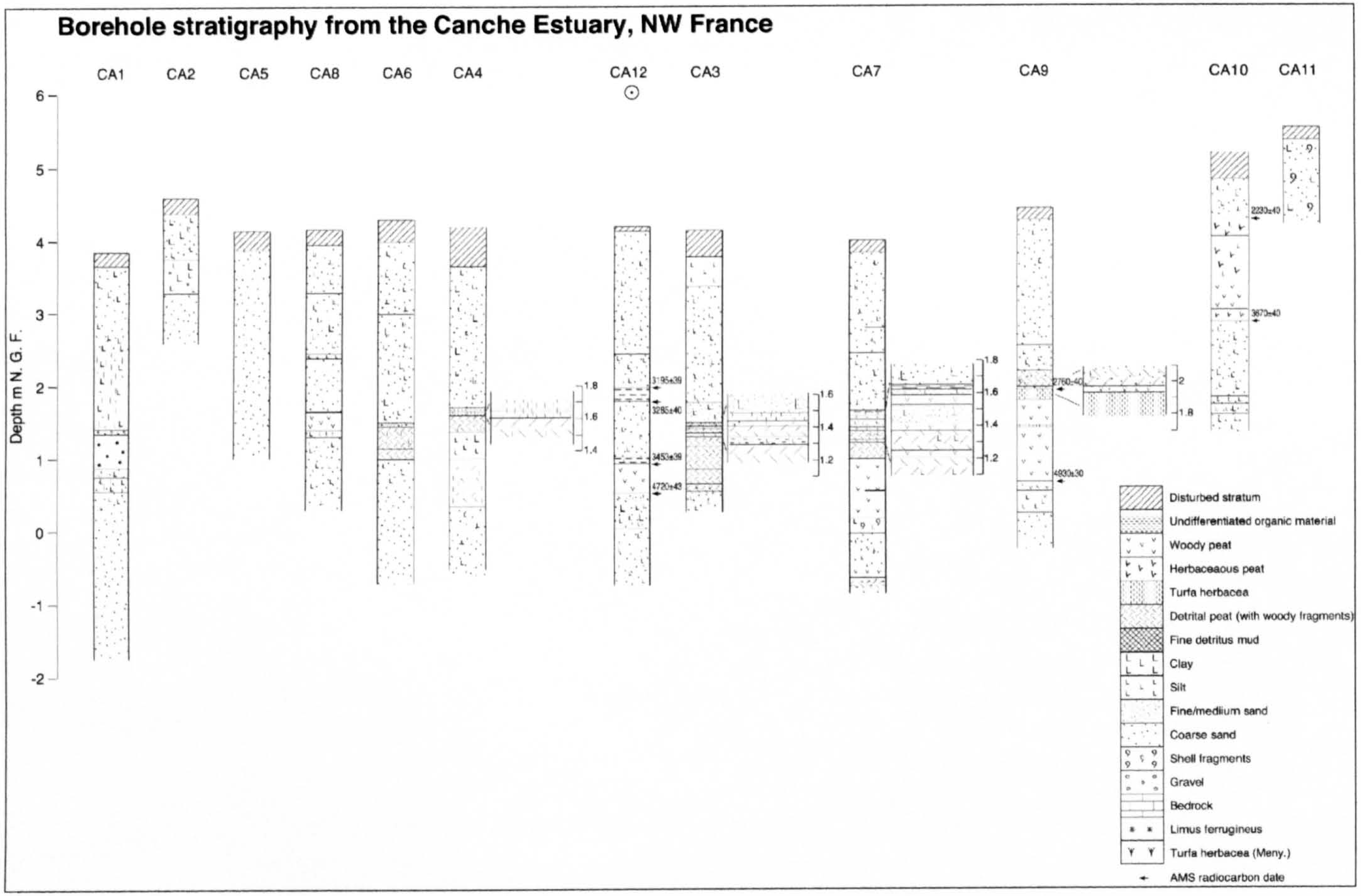


Fig. 5.1 Stratigraphic diagram of the Canche Estuary, Northern France.

Symbols are based upon the Troels-Smith classification (1955)

Boreholes CA4, CA12 (sample core), CA3 and CA7 were all similar in that two organic layers were recorded. The lowest unit was again sand, with some silt present. A peat deposit, up to 0.5m thick, overlay the sand and silt layer. This was followed by a silty clay unit, which separated the two peat layers, the thickness of which varied, but reached 0.5m in CA4 and CA12. In CA3 and CA7 this layer was also present but was much thinner. The upper organic layer followed the silty clay layer but was much thinner in CA3 than in CA7. In many of the cores this organic unit tended to be more herbaceous than woody.

As the height of the land rose towards the valley side (boreholes CA9, CA10 and CA11) another change in the stratigraphy was found. The lower sand deposit was still present, as was the shift to more silty sediment. However in cores CA9 and CA10 no silty clay layer was observed. The peat layer was much thicker and several changes in the colour and type of peat were noted, suggesting changes in the height of the water table at the time of sediment deposition. The upper silty sand unit was again recorded; however, its thickness had decreased significantly to only 0.5m in CA10 compared with over 2m in previous cores. The final core, CA11, was composed entirely of a sand deposit with silt and visible molluscs present.

The sample core, CA12 (see Table 5.2), was selected because it represented the greatest number of sediment changes and therefore provided a greater number of potential sea-level index points. Ten stratigraphic units were identified. The lowest unit CAI was a fine to medium grained grey sand with some silt present. This unit then progressed into blue-grey sandy silty clay (Unit CAII). Unit CAIII, above, represented a gentle transition from silty clay to the woody peat (CAIV). The peat in unit CAIV was a well humified dark brown woody peat. The peat progressed into a silty peat transitional unit (CAV) and then into the overlying grey silty sand unit (Unit CAVI). A sharp transition marked the onset of the upper organic unit (CAVII) but it was not thought to be erosional. This thin unit was composed of undifferentiated organic matter and was very decomposed. Again, an abrupt contact marked the beginning of unit CAVIII, a grey silt with sand. Unit CAIX, a pale grey sandy silt with organic flecks and signs of oxidation overlay this.

Unit	Depth NGF	Description
CAX	4.39 – 4.13	**Topsoil**
CAIX	4.13 – 2.45	**Pale sandy silt showing signs of oxidation and some organic flecks** Ag3 Ga1
CAVIII	2.45 – 1.98	**Grey silt with sand** Ag3 Ga1+
CAVII	1.98 – 1.81	**Undifferentiated organic deposit** Sh^4 4
CAVI	1.81 – 1.08	**Grey silty sand with organic flecks** Ag2 Ga2
CAV	1.08 – 0.95	**Silty peat transition** Ag2 Sh^4 2
CAIV	0.95 – 0.53	**Dark brown well humified woody peat** Tl4
CAIII	0.53 – 0.44	**Silty clay transition with shell remains** As2 Ag1 Ga1
CAII	0.44 – 0.104	**Blue-grey sandy silty clay** As2 Ag1 Ga1
CAI	0.104 - -0.70	**Grey sand with some silt present** Ga3 Ag1

Table 5.2 Description of the sample core from the Canche Estuary

Mid- to late-Holocene sea-level changes at the Canche based upon the stratigraphic descriptions

The sediments recorded at the Canche clearly show that a number of changes in coastal sedimentation have taken place.

Unit CAI: Sand with silt

The lower deposit of sand and silt (unit CAI) could be indicative of a marine or fluvial deposit. Biostratigrahic data are required to determine its depositional origin.

Unit CAII: Blue-grey sandy silty clay

The transition into unit CAII, the blue-grey sandy silty clay, indicates a gradual fall in relative sea-level, allowing finer-grained sediments to have been deposited, possibly revealing estuarine or lagoonal conditions.

Unit CAIII: Transition silty clay

This transition reveals that the site was still under a marine depositional environment, with shell remains clearly visible.

Unit CAIV: Woody peat

The transition into the first organic layer provides the first potential regressive overlap, with the peat deposit probably forming gradually under a slowly falling relative sea-level.

Unit CAV and CAVI: Transition silty peat and silty sand layer

A return to more marine conditions can then be seen by the onset of silt deposition in units CAV and CAVI, with organic flecks in unit CAV showing that sea-level remained low enough for vegetation to continue to colonise.

Unit CAVII: Undifferentiated organic matter

A fairly rapid final regressive event can be seen by the return of organic sediments in unit CAVII. The sediment was composed of undifferentiated organic matter and was well-decomposed indicating peat deposition under brackish conditions.

Unit CAVIII: Silt and sand

The onset of the sediments in unit CAVIII implies that a fairly rapid rise in sea-level took place, with the site returning to an inter-tidal setting as shown by the presence of both silt with sand.

Unit CAIX: Sandy silt

A reduction in sea-level must have followed unit CAVIII, as unit CAIX showed signs of oxidation staining and organic flecks, suggesting periods of drying out .

Of particular interest is the presence of the blue-grey sandy silty clay deposit (Unit CAII). A similar unit to this was recorded by the BRGM in borehole 00167X0114/F1. Previous research (Long & Innes, 1993) considered the blue-grey clay recorded at Romney to be a lagoonal deposit, however the deposit at the Canche had a much higher sand content than the sample collected from south east England suggesting a continued marine presence. The deposit could possibly represent an inter-tidal depositional environment, where the site was regularly flooded at high tide.

The stratigraphic record from the Canche points to evidence which indicates that two marine transgressions and two marine regressions may have taken place during the mid- to late-Holocene. However, palaeoecological information is required before any conclusions about sea-level change can be drawn.

5.2 Pollen data

Pollen preservation in the sample collected from Villiers was excellent and provided a good basis to begin understanding the sea-level history of the area. The following section has been divided into stratigraphic units. The sampling strategy employed meant that the use of local pollen assemblage zones in this case was not considered appropriate. Once again the palaeoecological data has been constrained by stratigraphic units in order to aid the comparison between sites and biostratigraphic indicators. Samples were taken from each of the organic stratigraphic units recovered in the sample core, but were concentrated across the stratigraphic boundaries. Fig. 5.2 presents the pollen diagram for the site and Table 5.3 provides a summary of the main shifts in the pollen record. Each stratigraphic unit will be discussed, an explanation for the use of stratigraphic divisions is provided in Chapter Four.

Unit	Stratigraphy	Biostratigraphy	Depositional Environment
CAX	Topsoil	No samples taken	
CAIX	Sandy silt	Poor preservation	
CAVIII	Grey silt with sand	Chenopodiaceae and Gramineae dominate but *P. lanceolata* was also present	Salt marsh – open ground
CAVII	Organic turfa	Low counts	Wet – high marsh
CAVI	Grey silty sand	No pollen remained	
CAV	Silty peat transition	Gramineae, Chenopodiaceae and Aster-type but in low counts	Salt marsh
CAIV	Lower peat	Gramineae, Chenopodiaceae	Salt marsh
CAIII	Silty peat	Gramineae and tree pollen only	Open - woodland
CAII	Blue-grey sandy silty clay	Gramineae & Chenopodiaceae dominate plus *Plantago lanceolata* and some *Corylus* and *Betula*	Open – Salt marsh Possibly human influence
CAI	Grey sand with some silt present	No samples taken	

Table 5.3 Summary of pollen data from the Canche Estuary

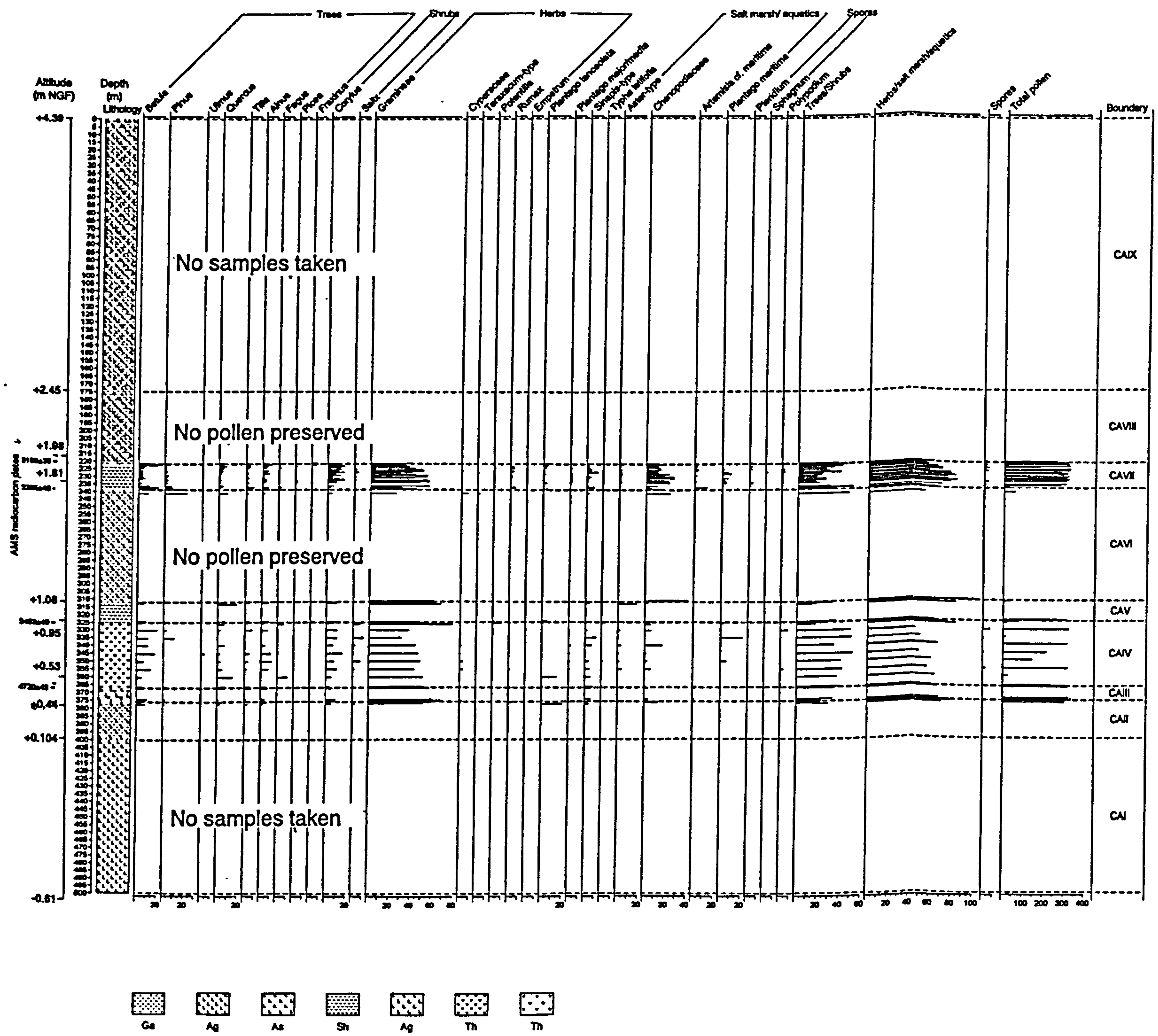


Fig. 5.2 Pollen diagram for the Canche sample core

Zones are based upon stratigraphic boundary changes and species are divided into trees, herbs, saltmarsh/aquatics and spores

Unit CAI: Lower sand unit (-0.70 - 0.104m NGF)

No pollen samples were taken from this unit.

Unit CAII: Lower sandy silt (0.104 – 0.44m NGF)

Samples were taken from just below the stratigraphic contact with the silty peat layer. Inorganic matter dominated the unit and few samples contained fossil pollen. The samples revealed a dominance by open habitat species. Gramineae dominated, accounting for up to 60% of the total pollen. Trees accounted for 30% with *Betula*, *Corylus* and *Alnus* dominating. This suggests that the area was mostly clear at this time, perhaps with pollen from surrounding woodland being blown-in. Also of importance to note is the presence of *Plantago lanceolata*, suggesting a possible anthropogenic influence on the land or waste ground. Plus, Chenopodiaceae and *Artemesia cf. maritima* pollen grains were present, usually indicative of a salt marsh.

Unit CAIII: Lower silty peat (0.44 – 0.53m NGF)

This unit represents the transition from the lower sandy silt into the lower peat deposit. Again the pollen record showed a dominance by open ground species, with Gramineae accounting for up to 70% of the total pollen count. Tree and shrub pollen reached 35% in total, with *Corylus*, *Betula* and *Alnus* dominating, all of which will grow on damp or moist deep soils. Chenopodiaceae was not recorded throughout the unit suggesting that it is not a salt marsh deposit. However, grains of Chenopodiaceae and *Artemesia* were recorded at the stratigraphic boundary with the lower peat (CAIV), indicating the presence of a salt marsh and possibly marking changes in the relative sea-level.

Unit CAIV: Lower peat (0.53 – 0.95m NGF)

The lowest samples continued to be dominated by open ground species. Gramineae continued to dominate with the occasional *P. lanceolata*. At 3.55m depth Chenopodiaceae appears again and continues to be present throughout much of the unit. This combination of high Gramineae levels with Chenopodiaceae accompanying it indicates that a salt marsh was present at this time. Also at this time, the proportion of tree pollen rises and at 3.50m depth *Salix* occurs in significant quantities for the first time. The presence of *Salix* along with *Alnus*, *Betula* and *Corylus* suggests that either the area was probably waterlogged at the time of sediment accumulation or that a stream or river was present nearby. At 3.60m depth *P. lanceolata* disappears from the record, however Chenopodiaceae continued to be recorded as did *Aster*-type, albeit in small amounts. Very low occurrences of *Rumex* and Cyperaceae were also noted, suggesting human activity at the site had declined. The pollen record throughout the unit remained fairly consistent until the boundary with the upper silty peat, when a peak in Gramineae occurred.

Unit CAV: Upper silty peat (0.95 – 1.08m NGF)

Pollen preservation was poor throughout this unit and it was not possible to achieve full counts. Gramineae, Chenopodiaceae and *Aster*-type were all present as can be seen at the stratigraphic boundaries on the pollen diagram, but not in significant quantities. Due to the highly inorganic nature of this sediment, it was not possible to draw any firm conclusions from the pollen record, but the record strongly suggests perimarine sedimentation.

Unit CAVI: Middle sandy silt (1.08 – 1.81m NGF)

No pollen was recorded from this sedimentary unit. At the upper stratigraphic contact, a low pollen count was achieved which showed the presence of Gramineae and Chenopodiaceae. This suggests that the depositional environment had not changed significantly from the previous unit.

Unit CAVII: Undifferentiated organic matter (1.81 – 1.98m NGF)

From the onset of this unit there is a clear dominance by Gramineae and Chenopodiaceae. Tree pollen consistently remains at around 20% of the total pollen with *Betula, Corylus, Alnus* and *Tilia* all present. Throughout the unit Gramineae and Chenopodiaceae dominated, accounting for 40% and 25% respectively. *Artemesia cf. maritima* and *Aster*-type were also present, both of which are known to grow on or near salt marsh deposits. Mid-way through the unit at 2.34m depth *Plantago maritima* appeared for the first time suggesting a strong marine influence. Towards the top of the unit there was a rise in tree pollen. *Betula, Corylus* and *Quercus* all increased and Gramineae and Chenopodiaceae both declined. At 2.27m depth, *Pteridium* appeared for the first time, indicative of open dry land, and shortly afterwards *P. lanceolata* returned. However, the lack of wood remains throughout this organic unit, suggests that the woodland pollen may have been transported from elsewhere in the valley or valley sides, where the altitude of the land would have allowed woodland species to persist, irrespective of any changes in sea-level.

Unit CAVIII: Upper sandy silt (1.98 – 2.45m NGF)
Only a single sample provided pollen data, near the lower contact, recording similar pollen to that revealed in Unit CAVII. No further samples contained any pollen.

Unit IX: Upper silt (2.45 – 4.13m NGF)
No samples were obtained from this unit.

Summary of pollen data
The pollen data collected from borehole CA12 provided good evidence for a number of changes in the depositional environment at Villiers. The pollen recorded in unit CAIII, the silty peat transition, indicated that a salt marsh was present at this time. This places sediment deposition between mean tidal level (MTL) and mean high water spring tide (MHWST), suggesting a relative fall in sea-level between Units CAII and CAIII. The onset of the woody peat deposit (unit CAIV), also allows a relative fall in sea-level to be inferred, with a shift in the pollen record from salt marsh and open ground species to more woodland species. The first possible marine transgression is recorded at the transitional unit CAV, marked a return to salt marsh conditions. Marine conditions appear to have remained, as the sediment changed to sand and silt. However, a relative fall in sea-level is believed to have taken place. The pollen from unit CAVII suggested a high marsh deposit. The final marine transgression is suggested by the onset of silt and sand deposition (CAVIII).

5.3 Diatom data

Samples were taken from each stratigraphic unit, and the following descriptions are constrained by stratigraphic unit, although changes within the unit are discussed. Fig. 5.3 shows the diatom diagram graphically and Table 5.4 presents a summary of the main findings for each unit.

Unit	Stratigraphy	Biostratigraphy	Depositional Environment
CAX	Topsoil	No samples taken	
CAIX	Sandy silt	Poor preservation	
CAVIII	Grey silt with sand	*P. sulcata, T. navicularis* and *A. delicatula*	Marine/Brackish - tidal flats
CAVII	Organic turfa	*A. delicatula, D. didyma* Melosira-Sulcata group dominant	Brackish - salt marsh or low marsh
CAVI	Grey silty sand	*P. sulcata, R. amphiceros* and *D. surirella*	Marine
CAV	Silty peat transition	*A. delicatula* and *P. sulcata* dominate	Marine/Brackish - tidal flats
CAIV	Lower peat	Only a few samples *Tryblionella navicularis* and *Navicula cari var cinta*	Brackish
CAIII	Silty peat	*P. westii, D. crabro* and *A. senarius* with some freshwater taxa	Brackish
CAII	Blue-grey sandy silty clay	*Paralia sulcata, Psuedopodosira westii* and *Raphoneis amphiceros*	Marine – tidal flats
CAI	Grey sand with some silt present	No samples taken	

Table 5.4 Summary of diatom data collected from the sampler core at Villiers

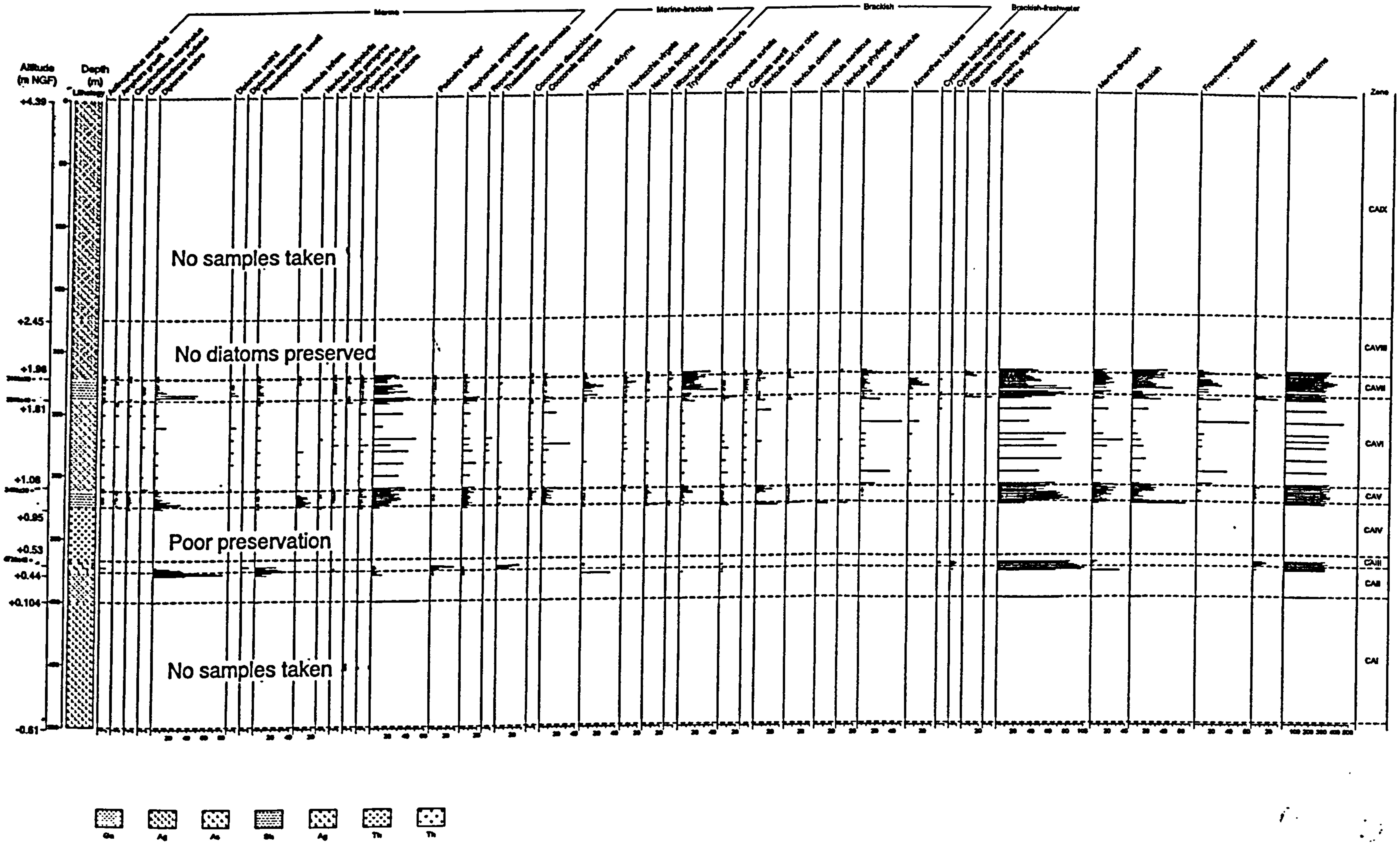


Fig.5.3 Diatom diagram for the Canche Estuary

Zones are based upon stratigraphic boundary changes and species are divided into marine, marine-brackish, brackish, tidal flats and freshwater

Unit CAI: Lower sand (-0.70 – 0.104m NGF)

No samples were taken from this unit.

Unit CAII: Lower sandy silt (0.104 – 0.44m NGF)

The lowest samples were dominated by the marine diatom *Paralia sulcata*, a polyhalobous tychoplanktonic species common to all coastal sites in south east England (Hendey, 1964). This dominated the lowest sample examined, accounting for 50% of the total diatom sum. It is frequently found on sandy flats (Zong & Horton, 1998, 1999) and was part of the "Melosira-sulcata group" (Vos & de Wolf, 1988). *Raphoneis amphiceros* and *Delphineis surirella* were also present, both of which favour mid- to high-salinity environments (Vos & deWolf, 1988; Zong & Horton, 1998). The following samples from this unit all showed dominance by *Diploneis crabro*, a marine species. *Pseudopodosira westii*, a tychoplanktonic species often found in association with *P. sulcata*, accounted for 20% of the total diatoms recorded. These species all suggest that tidal flats, most likely sand flats, were present at the time of deposition, placing the deposit at or around MLT.

Unit CAIII: Lower silty peat (0.44 – 0.53m NGF)

The lower samples from this unit continued to show a similar record to that of the lower sandy silt, with *D. crabro, P. westii* and *P. sulcata* dominating. In addition *Thalassiosira condensata* and *Actinoptychus senarius* were also present, again suggesting a fully marine environment. However, at 3.70m depth there was a marked change in the taxa, shown by the occurrence of *Cyclotella keutzighiana* and *Cycoltella meneghiana*, both freshwater-brackish indicators (Hartley, 1986). At this time there was also a dramatic decline in the preservation of the diatom frustules coupled with an increase in the amount of organic flecks present in the sediment. This could possibly be indicative of a relative sea-level fall.

Unit CAIV: Lower peat (0.53 – 0.95 NGF)

Few diatoms were preserved within this unit other than at the stratigraphic boundaries. The lower boundary showed freshwater-brackish species dominating, whereas the upper boundary contained mainly brackish-favouring species, with *Tryblionella navicularis* and *Navicula cari* var. *cinta* present. The diatom species suggest that the sediment was deposited under mainly freshwater conditions, indicating the first major regressive overlap at Villiers. However, the occurrence of some brackish species also point to a continuing marine influence in the area, for instance the presence of tidal channels across a salt marsh could allow species to be washed-in and deposited.

Unit CAV: Middle silty peat (0.95 – 1.08m NGF)

Diatom analyses were undertaken every centimetre throughout this unit because the pollen record had not provided useful results. Diatom preservation throughout this unit was excellent, highlighting the value of using more than one palaeoecological indicator. The lower samples were dominated by marine-brackish diatom species, including many of the *Navicula* taxa and *Cocconeis speciosa*. *P. sulcata* was also present, increasing toward the top of the unit. However, it is well known that its filamentous chains allows it to be washed-in and therefore often appears to dominate the record, making a sample appear more marine than it actually is (Zong, 2000). The marine species *Navicula inflexa* was recorded for the first time in this unit, in quantities of up to 15%. Throughout the unit *R. amphiceros* and *D. crabro* were present, up to 10% and 30% respectively, supporting the theory that highly saline marine conditions were influencing the area at this time. Towards the centre of the deposit, around 320cm depth, a rise in the marine species can be seen, with *Opephora pacifica* and *Cocconeis disculoides* appearing for the first time. *P. sulcata, R. amphiceros* and *N. inflexa* continued to be present throughout, but levels of *A. delicatula* are seen to vary. *A. delicatula* is an important indicator as it occupies sandy tidal flats or low marsh deposits making it a useful marker for MHWST. Although the depositional environment remained highly saline throughout much of the unit, indicating a strong marine influence, it can clearly be seen that a number of changes relating to tidal position took place.

Unit CAVI: Upper sandy silt (1.08 – 1.81m NGF)

The early samples from this unit revealed a sharp increase in the tidal species with *Acnanthes delicatula* rising from 4% to 17%, coupled with a decline in *N. cari* var. *cinta* and *D. crabro*. The marine taxa *P. sulcata, R. amphiceros* and *D. surirella* were all present in high numbers, with total marine diatoms reaching 70% in some samples. Consistent levels of the marine-brackish species *Hantszchia virgata* and the brackish species *T. navicularis* were also recorded. The low levels of *P. westii*, often found with *P. sulcata*, indicates that it is not a low marsh or salt marsh deposit. It is therefore possible that the sediment was deposited under an intertidal environment, most likely sandy tidal flats, since diatoms from the "Melosira-sulcata group" (Vos & deWolf, 1988) were dominant.

Unit CAVII: Undifferentiated organic matter (1.81 – 1.98m NGF)

Initially *Diploneis crabro* was seen to dominate, with *A. delicatula* and *N. navicularis* also present in high numbers throughout the unit. This suggests that tidal flats were present at this time or perhaps the record shows that the diatom species responded slowly to changing conditions. *A. delicatula* also found on low marsh deposits, at or around MHWST, implies that a regressive event took place between unit CAVI and CAVII. At 1.87m NGF, *Diploneis crabro* declined rapidly from *c.* 40% to just 2% and the diatoms of the "Melosira-Sulcata group" (Vos & deWolf, 1988) were seen to dominate. The combination of *P.westii* and *P. sulcata* seen here is commonly recorded in modern day salt marsh assemblages from the UK (Vos & deWolf, 1988). *Diploneis didyma*, also seen to occur here, at *c.* 10%, suggests a tidal flat environment (Hendey, 1964). However, throughout the unit the occasional freshwater-brackish species was also recorded. This slightly mixed diatom record, mainly dominated by the "Melosira-Sulcata group", suggests that a salt marsh was present.

Unit CAVIII: Grey silt with sand (1.98 – 2.45m NGF)

P. sulcata, T. navicularis and *A. delicatula* returned in high numbers and dominated the lower part of this unit. These suggest that there was a return to more marine conditions, with tidal flats dominating the site once again. Unfortunately no diatom samples were recovered from the remainder of the unit or unit CAIX above.

Summary of diatom data

The diatoms revealed the blue-grey sandy silty clay (Unit CAII) to be a tidal flat deposit, indicating that marine conditions dominated. Unit CAIII, the silty peat transition, contains the first change from marine to freshwater diatoms, suggesting the first fall in relative sea-level. The first regressive overlap can be observed at the onset of the lower peat deposit, throughout which diatom preservation was poor. Unit CAV signalled a return to more marine conditions, probably a sand flat environment, shown by the presence of *A. delicatula* and *P. sulcata.* Marine diatoms remained dominant until unit CAVII, the undifferentiated organic matter, when the salt marsh diatom species were seen to increase. The final possible marine transgressive overlap is marked by the return of tidal flat species *P. sulcata, A. delicatula* and *T. navicularis* in unit CAVIII.

Diatom-based transfer function

Once again the diatom results were further analysed by calibrating the data using a diatom-based tidal level transfer function (Zong & Horton, 1998, 1999). The transfer function was applied to the sub-fossil data collected from the Canche Estuary (Table 5.5 and Fig. 5.4), where MHWST has a SWLI of 300 and MTL is 200. In order establish the altitude of the sample relative to ordnance datum, the SWLI were back-transformed using local MHWST and MTL (see Equation 5.1).

Depth	SWLI	Back transformed depth m NGF	Reference water level (MHWST +/-)
219	235	2.37	-2.70
220	238	2.50	-2.57
221	236	2.40	-2.67
222	236	2.41	-2.66
223	236	2.41	-2.66
224	227	2.04	-3.03
225	244	2.75	-2.32
226	245	2.80	-2.27
227	242	2.65	-2.42
228	243	2.68	-2.39
229	240	2.58	-2.49
230	240	2.56	-2.51
231	231	2.23	-2.84
232	249	2.96	-2.11
233	233	2.28	-2.79
234	269	3.77	-1.30
236	243	2.69	-2.38
237	240	2.57	-2.50
238	234	2.34	-2.73
239	248	2.91	-2.16
240	243	2.71	-2.36
241	238	2.48	-2.59
243	242	2.68	-2.39
260	246	2.82	-2.25
270	239	2.53	-2.54
275	240	2.58	-2.49
280	245	2.77	-2.30
290	247	2.86	-2.21
300	236	2.42	-2.65
310	243	2.71	-2.36
311	242	2.66	-2.41
313	249	2.94	-2.13
314	255	3.20	-1.87
315	244	2.73	-2.34

Continued on next page

Depth	SWLI	Back transformed depth m NGF	Reference water level (MHWST +/-)
316	247	2.88	-2.19
317	239	2.53	-2.54
318	239	2.53	-2.54
319	237	2.47	-2.60
320	238	2.51	-2.56
321	238	2.51	-2.56
322	238	2.52	-2.55
323	243	2.72	-2.35
324	250	2.99	-2.08
325	267	3.69	-1.38
326	269	3.77	-1.30
327	276	4.07	-1.00
373	257	3.29	-1.78
374	255	3.19	-1.88
375	257	3.28	-1.79
376	237	2.46	-2.61
377	239	2.54	-2.53
378	238	2.48	-2.59
379	255	3.22	-1.85
400	237	2.48	-2.59

Table 5.5 continued SWLI, back-transformed depth NGF and reference water level for samples taken from the Canche Estuary, Northern France

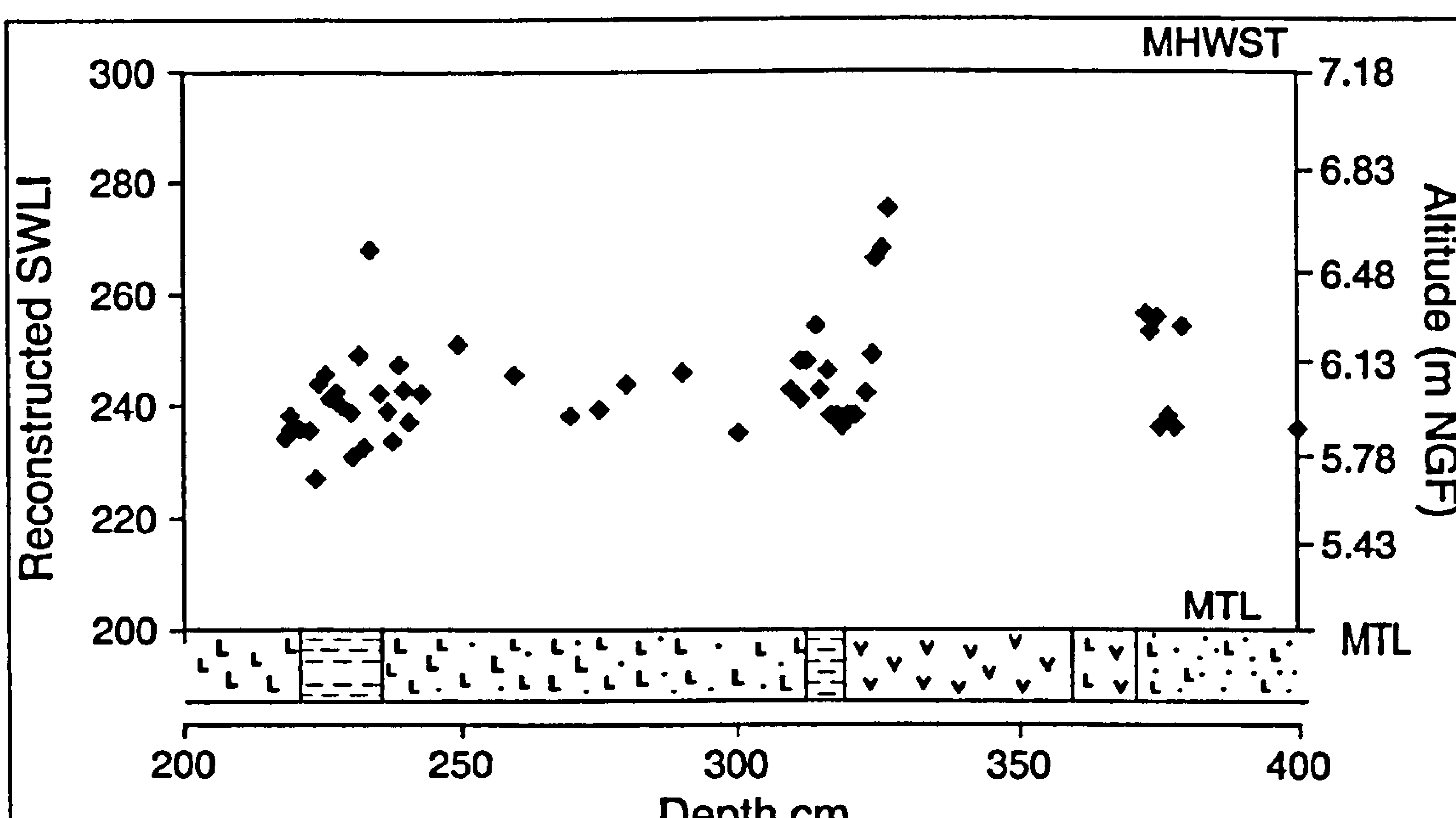


Fig. 5.4 Reconstructed SWLI based upon the diatom-based transfer function for the Canche Estuary, Northern France. MHWST has a SWLI of 300.

In the past, sea-level index points have been assumed to be indicative of past MHWST (Devoy, 1979; Heyworth & Kidson, 1982) and more recently the use of a transfer function is one method that has become available to establish the reconstructed tidal position with more accuracy. However, as will be demonstrated, this method is not without its limitations. The immediate point to note is that no values exceed MHWST. In fact most samples plot well below MHWST, even those from the regressive overlaps, which would expect to show a close proximity to or exceed MHWST. Upon closer examination it appears that this could be due to the species that were present in the samples not being present in the transfer function training set. Only 18 of the 34 taxa present in the fossil data set were present in the DBTF training set. Which once again makes the use of the results from the diatom-based transfer function limited, and this must be remembered when examining the following results.

The lower regressive overlap at +0.45m NGF (376cm depth) was assigned a SWLI of 237 which once back-transformed plots at MHWST -1.79m. At this depth only 2 of the 7 species recorded in the fossil dataset were present in the training set, that is only 28% of the total recorded. This sample was dominated by the marine species *Diploneis crabro* and *Pseudopodosira westii*, species usually found in highly saline environments, often in association with *P. sulcata* on sandy tidal flats. Neither of these species were present in the training set developed by Zong & Horton (1998). This would have meant that *Paralia sulcata* emerged as the dominant species in the transfer function, a species known to be washed-in by tides. In addition to this, none of the freshwater diatom species, *Cyclotella keutzighiana* and *Cyclotella distinguenda* that were present in the sample were present in the training set. This caused the DBTF to produce a lower SWLI, suggesting deposition took place well below MHWST, whereas the diatoms recorded in the fossil dataset suggest deposition at or around MHWST. If the freshwater species had been present in the training set, it may have resulted in a reconstructed tidal level of around or above MHWST.

The transgressive contact between units CAIV and CAV, at 329cm depth, did not actually contain any diatoms. The nearest sample that did produce a diatom record was at 327cm depth within the silty peat unit CAV. In this sample 48% of the fossil species recorded were present in the training set, which would have given a more reliable result. The DBTF produced a SWLI of 276, which plotted at MHWST-1.0m, suggesting a relatively high altitudinal position. However, because the species *Diploneis crabro* was absent from the training set, it is thought that *P.sulcata*, *Raphoneis amphiceros*, *Opephora pacifica* and *Navicula phyllepta* were over-represented in the transfer function, thus again lowering the reconstructed SWLI.

The upper regressive overlap into CAVII had a SWLI of 248, once again plotting well below MHWST at -2.16m. 15 species were recorded in the fossil dataset, of which 9 were present in the training set that is 60%. The high frequencies of *P. sulcata* and *R. amphiceros* could explain why the SWLI was much lower than had been expected, based on the results of the biostratigraphic analysis. Coupled with the high levels of *Delphineis surirella*, which has an extremely large SWLI range and thus altitudinal habitat range (Zong & Horton, 1998).

The upper transgressive overlap at 222 cm depth produced a SWLI of 236, which plots at MHWST -2.01m, indicating a return to more marine conditions. Of the 18 species present in the sample, 11 were contained in the training set, again giving a 60% presence in the training set. However, since most of the dominant species (*P. sulcata*, *Nitzschia navicularis* and *Acnanthes delicatula*), species that are known to inhabit tidal flats at or around MTL, were contained in the training set, the DBTF appears to have produced better-quality results at this overlap than at many of the others. Previous interpretations have always assumed that a transgressive overlap represents deposition at or around MHWST. However, why is it not possible that the sediment was deposited under much lower tidal conditions? If the diatoms present show a tidal flat environment, then why should it be assumed that simply because the stratigraphy implied deposition at or around MHWST, that the environment could not have been tidal flats? This would be a feasible explanation if the biostratigraphy showed the peat deposit to be a saltmarsh, thus placing its altitude between MTL and MHWST. This would mean that the stratigraphic overlap would not be at or above MHWST and that a relatively small rise in relative sea-level could result in a more marine sedimentary environment, such as a tidal flat. However, there would need to be overwhelming modern-day and fossil evidence to support such a shift from an organic deposit, which has formed above or around MHWST, to an inorganic deposit, which formed closer to MTL, as this would require a period of rapid submergence.

The discrepancies observed between the biostratigraphic data and the transfer function data at the regressive overlaps could be the result of the species present in the data set. Many of the freshwater species were absent from the training set used in the diatom-based transfer function, placing samples at lower tidal levels than they would actually have been had the freshwater diatoms been included. It is likely that because the training set for the DBTF was collected from north east England, different diatom species have been encountered. If a modern analogue training set were to be collected from the present-day lower and middle salt marsh at the Somme, for example, a new transfer function could be developed allowing a more accurate data set to be used.

The dominance by the tychoplanktonic and planktonic species that were recorded at the Canche, clearly affected the way in which the transfer-function performed. As a direct result of this the findings from the DBTF have not been used in any further interpretation of the results. In order for the DBTF to be applied to the data sets from northern France further modern-day analogues from a variety of sites would need to be collected.

5.4 Foraminiferal data

Fig. 5.5 shows the foraminiferal percentages with the stratigraphic zones marked on, and the foraminiferal data divided into agglutinated and calcareous species. Table 5.6 presents a summary of the foraminiferal results for each stratigraphic unit. It can be seen that the foraminiferal records from the Villiers sample core were varied. Some of the sandy sediments revealed excellent records, however many of the other units did not contain sufficient tests for depositional environments to be assigned to a unit.

Generally foraminiferal abundance was low but preservation was good. Data have, therefore, still been presented and used as a method of interpreting sediments. Percentages have been calculated, but total counts have been included to highlight where abundances were low.

Unit CAI: Lower sand (-0.70 – 0.104m NGF)

Samples taken from this unit did not contain any foraminifera.

Unit CAII: Lower sandy silt (0.104 – 0.44)

Foraminifera were not recovered from all sampled depths in this unit. However, those samples that did contain tests showed that calcareous types, including *Ammonia beccarii* and *Nonion* *depressulus*, dominated. Both these species are common to Britain and are usually found on sandy tidal flats or occasionally in low marsh sediments (Murray, 1973).

Unit	Stratigraphy	Biostratigraphy	Depositional Environment
CAX	Topsoil	No samples taken	
CAIX	Sandy silt	No samples remained	
CAVIII	Grey silt with sand	*A. beccarii* and *N. depressulus*	Nearshore environment
CAVII	Undifferentiated organic matter	*J. macrescens*	Salt marsh
CAVI	Grey silty sand	*Elphidium williamsonii, A. beccarii* and *N. depressulus*	Tidal flats
CAV	Silty peat transition	No foraminifera	
CAIV	Lower peat	No foraminifera	
CAIII	Silty peat	*Trochammina inflata* and *Jadammina macrescens*	Salt marsh
CAII	Blue-grey sandy silty clay	*Ammonia beccarii* and *Nonion depressulus* - Calcareous	Marine – tidal flats
CAI	Grey sand with some silt present	Poor preservation	

Table 5.6 Summary of foraminiferal results from the Canche Estuary

Unit CAIII: Lower silty peat (0.44 – 0.53m NGF)

It was only possible to prepare a single sample from this unit due to the amount of sediment required to recover foraminifera tests. *Trochammina inflata* and *Jadammina macrescens* dominated, suggesting this unit was a low marsh peat deposit. *T. inflata* is found between MHW and MHWST in marsh or tidal flat deposits and *J. macrescens* is known to be a salt marsh species (Haslett, 1997) also found between MHW and MHWST.

Unit CAIV: Lower peat (0.53 – 0.95m NGF)

This unit did not contain any foraminiferal remains and is therefore thought to be a freshwater deposit, showing no signs of ever having been a salt marsh. This corresponds well with the pollen and diatom data, which also suggest a freshwater deposit.

Unit CAV: Upper silty peat (0.95 – 1.08m NGF)

No foraminifera were recorded from this unit, making it impossible to draw any conclusions.

Unit CAVI: Middle sandy silt (1.08 – 1.81m NGF)

Calcareous species dominated with *Elphidium williamsonii, A. beccarii* and *N. depressulus* all present in high numbers. All of these indicate that a tidal flat environment, with palaeo-tidal level at or around MLT, existed at the time of deposition.

Unit CAVII: Undifferentiated organic matter (1.81 – 1.98m NGF)

Foraminiferal counts from this deposit were low; less than 10 tests, with only a few *Jadammina macrescens* and *T. inflata* were recorded. Although the data is insufficient to assign a depositional environment with any certainty, it is likely that a salt marsh was present, as suggested by the presence of *J. macrescens.*

Unit CAVIII: Upper sandy silt (1.98 – 2.45m NGF)

Two samples were taken from this unit, both of which showed a dominance by calcareous species. *Ammonia beccarii* and *Nonion depressulus* recorded the highest values, with *Elphidium williamsonii* and *T. inflata* present in lower amounts. These species suggest a highly saline environment, almost certainly tidal flats. However, *T. inflata* is also found between MHW and MHWST, suggesting a lower sea-level than shown by the other foram species. However, *T. inflata* has also been recorded on near-shore marine environments because non-living tests have been washed in (Murray, 1971).

Unit CAIX: Upper silt (2.45 – 4.13m NGF)

No samples were recorded from this unit.

Summary of foraminiferal data

Since no foraminiferal samples were obtained from Unit CAI or CAII, the summary of the data begins at the top of Unit CAII. The foraminifera recovered from the overlap between Unit CAII and CAIII, the blue-grey sandy silty clay revealed sediment deposition to be marine-dominated, most likely representing a sand flat deposit. Following this, a fall in relative sea-level took place, permitting the colonisation of a salt marsh, shown by the presence of *Jadammina macrescens* and *Trochammina inflata.* This is thought to have been followed by a further reduction in sea-level, resulting in the deposition of the peat unit. The lack of foraminiferal data in unit CAIV, supports the theory of a freshwater environment at this time. Sea-level remained low until the silty peat unit was deposited, when a rise in sea-level caused the return in unit CAVI of the calcareous types *Ammonia beccarii, Nonion depressulus* and *Elphidium williamsonii*, all found on tidal flat environments. A second marine regression followed, resulting in the formation of a salt marsh, shown by the presence in unit CAVII of *J. macrescens*, though this was soon followed by the final marine transgression, shown by the return of *A. beccarii* and *N. depressulus*.

5.5 Summary of palaeoecological data

The results of the palaeoecological analyses are now discussed together, in order to provide a summary of all the findings from the Canche and compare the different techniques. Fig. 5.6 below is a summary of the pollen, diatom and foraminiferal data collected from the Canche Estuary. These have then been sub-divided, with pollen divided into tree/shrub pollen, salt marsh pollen and freshwater/aquatic pollen, diatoms divided into marine, marine-brackish, brackish, freshwater-brackish and freshwater and foraminifera divided into calcareous (marine) and agglutinated (salt marsh) types.

Unit CAI: Grey sand with silt (0.104 - -0.70m NGF)
The sediment would suggest that deposition took place under marine conditions, with some foraminifera recorded. However, preservation was poor throughout this unit, making it impossible to confirm a depositional environment.

Unit CAII: Blue-grey sandy silty clay (0.104 – 0.44m NGF)
Diatoms indicated that the sediment was under marine influence at the time of deposition. From the diatom records it was possible to confirm that the sediment was laid down under marine conditions, but not to assign a specific palaeo-tidal level, unless the SWLI from the diatom transfer function is included (MHWST –1.79m).

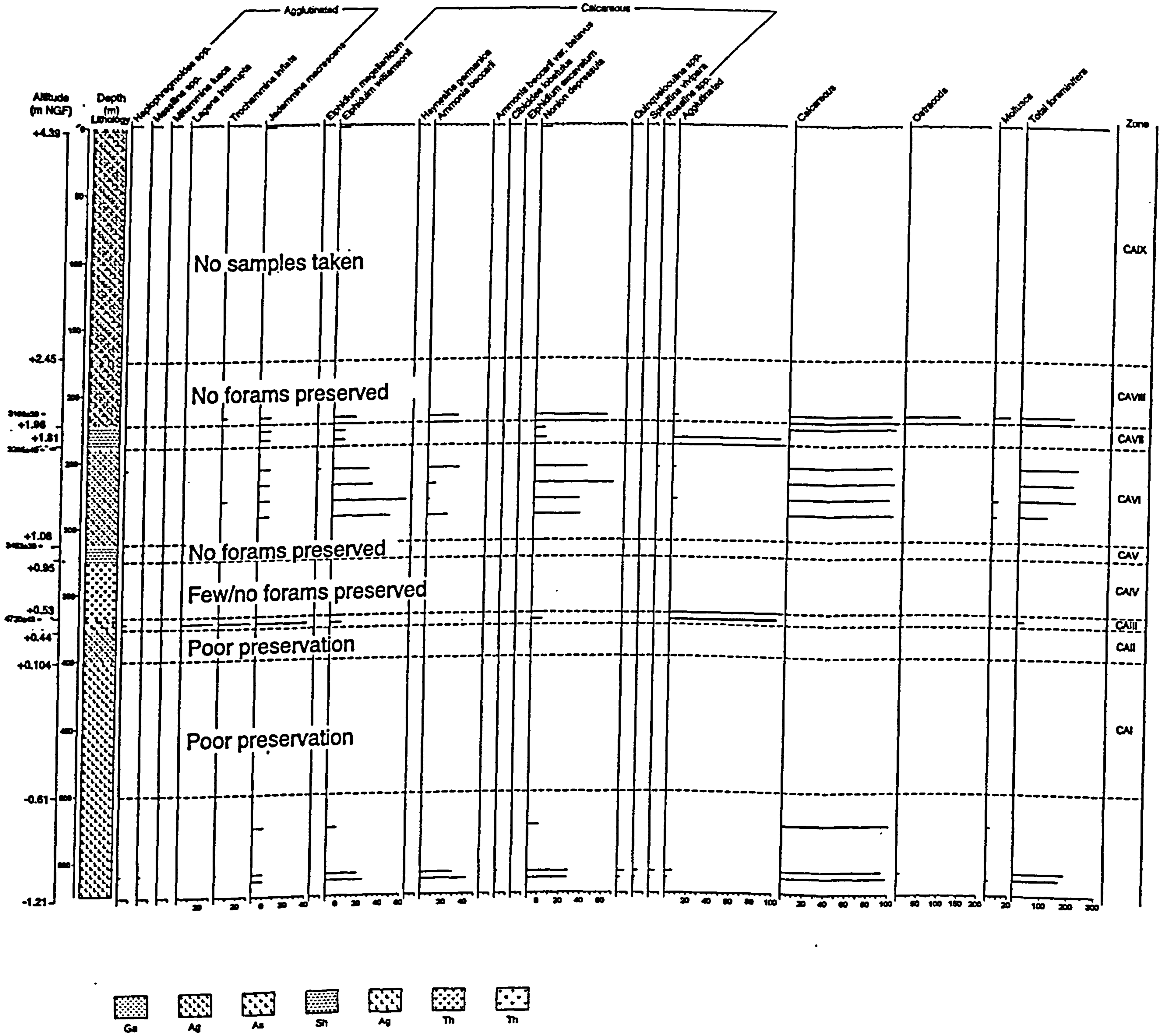


Fig. 5.5 Diagram to show foraminiferal data recorded from the Canche Estuary.
Zones are based upon stratigraphic units and species have been divided into agglutinated and calcareous

Unit CAIII: Lower silty peat (0.44 – 0.53m NGF)

The presence of Gramineae and Chenopodiaceae pollen grains signified a change in sea-level, suggesting the presence of open ground species, probably indicating a salt marsh. Diatom counts were low, providing little additional information. Foraminiferal preservation was also poor, with just a few *T. inflata* and *J. macrescens* recorded. However, these species are found to inhabit altitudes between MHW and MHWST, the low marsh. This ties in well with the pollen record, suggesting that this silty peat unit represents a salt marsh deposit, suggesting a fall in sea-level.

Unit CAIV: Lower peat (0.53 – 0.95m NGF)

The diatoms and foraminifera provided no useful record for this unit, with many levels containing zero counts. However, the pollen provided a continuous record of the vegetation changes that were occurring at this time, showing a shift from wet, open ground to an environment where anthropogenic impacts could be detected. Levels of *Alnus* declined towards the upper part of the unit, suggesting a relative fall in sea-level had taken place. However, toward the upper boundary of this unit, brackish and marine diatoms start to be recorded, suggesting that the area was once again being influenced by marine activity. The end of the unit clearly marks a rise in relative sea-level.

Unit CAV: Middle silty peat (0.95 – 1.08m NGF)

Preservation of the diatom frustules was sufficient to allow the tidal level to be estimated. The presence of *A. delicatula* suggested that at this time low marsh or tidal flats were present, placing sea-level at half way between MHWST and MTL. No fossil pollen or foraminiferal tests were preserved in this deposit, which meant interpretations could only be based upon the diatom data.

Unit CAVI: Middle sandy silt (1.08 – 1.81m NGF)

The diatoms suggested that the site was intertidal sand flats at around MLT, and the foraminifera appear to support this. The change in depositional environment suggests that the level of the sea had risen slightly, inundating the area. The foraminiferal record was dominated by calcareous species, in particular those which favour the sub-tidal or tidal flat altitudes.

Unit	Stratigraphy	Biostratigraphy	Depositional Environment
CAX	Topsoil	None	
CAIX	Sandy silt	None	
CAVIII	Sandy silt	Chenopodiaceae & Gramineae were present in high percentages. The diatom record was dominated by *P.sulcata* & *A. delicatula* and calcareous foramimifera dominated with *N. depressulus* & *A. beccarii*	Marine environment Tidal flats / salt marsh
CAVII	Undifferentiated organic matter	Chenopodiaceae & Gramineae dominated the pollen record. Marine-brackish diatoms were present in high percentages and a mixture of agglutinated and calcareous foraminifera species were recorded.	Low marsh
CAVI	Sandy silt	Chenopodiaceae & Gramineae were present in high values. Marine diatoms and calcareous foraminifera dominated	Marine environment Tidal flats or low saltmarsh
CAV	Silty peat	Poor pollen and foraminifera preservation. Marine and brackish diatoms were present with *P. sulcata* & *D. crabro* dominant	Marine - brackish Inter-tidal zone
CAIV	Peat	Trees plus Gramineae and Chenopodiaceae dominated the pollen record. No diatoms or foraminifera were preserved	Terrestrial Wet woodland pollen to open to salt marsh transition through the peat deposit
CAIII	Lower peat/sandy silt transition	Gramineae and tree pollen was dominant. Marine to brackish shift in diatoms species observed. Agglutinated foraminifera including *T. inflata* and *J. macrescens*	Brackish High/low marsh
CAII	Blue-grey sandy silty clay	Gramineae & Chenopodiaceae + *Plantago lanceolata* were present in significant quantities. Marine diatoms and calcareous foraminifera dominated.	Marine Salt marsh
CAI	Sand with silt	None	

Table 5.6 Summary of palaeoecological data from the Canche

Unit CAVII: Undifferentiated organic matter (1.81 – 1.98m NGF)

Three distinct phases can be seen throughout this thin unit. The lower samples showed a dominance by marsh pollen types, marine and brackish diatoms and agglutinated foraminifera. This would suggest that deposition was between MTL and MHWST. In particular the presence of Chenopodiaceae and Gramineae pollen along with the combination of *P. westii* and *P. sulcata* in the diatom record point to the existence of a salt marsh at this time. However, it must again be noted that these diatom species are known to be subjected to washing-in. The few examples of *J. macrescens* that were recorded also suggested it was a salt marsh deposit. A shift can then be seen whereby saltmarsh pollen peaked, but marine diatoms declined, with the introduction of some freshwater-brackish diatom species. A third shift then appears to have taken place, shown by a rise in tree/shrub pollen, indicating a shift to a more terrestrial environment.

Unit CAVIII: Upper sandy silt (1.98 – 2.45m NGF)

Diatom and pollen preservation was poor throughout this unit, a common problem in the upper oxidised horizons of coastal deposits, thought to result from rapid post-depositional dissolution when iron oxyhydroxides are present (Mayer *et al.* 1991). However, the foraminiferal records indicated a rise in relative sea-level. The presence of *A. beccarii, N. depressulus, E. williamsonii* and *T. inflata* suggest that tidal flats were present at this time, at around MTL.

The first negative tendency can be seen to occur in the sample core BH CA12 at the stratigraphic boundary change between Unit CAI and Unit CAII. However, palaeoecological data revealed that the first major relative sea-level fall took place at the boundary between Unit CAII and Unit CAIII. The first positive sea-level tendency then took place at the end of Unit CAIII, shown by the onset of the transitional silty peat unit (CAIV) and the return of intertidal diatom species, which continued into unit CAV. A second negative sea-level tendency can be observed at the stratigraphic boundary between unit CAVI and CAVIII, the onset of the undifferentiated organic matter. Only a slight rise in sea-level occurred at this time, shown by the presence of salt marsh pollen taxa, indicating a continuing tidal influence. The final positive sea-level change is marked by the return to silt and sand, representing tidal flat deposition at or around MTL.

5.6 AMS radiocarbon dating

In total, eight AMS radiocarbon dates were obtained from the samples collected at Villiers (Table 5.8). Four of these were taken from BH CA12, the sample core, dating two regressive and two transgressive overlaps. The first regressive overlap was dated at 4720 ± 43 years, followed by the first transgressive overlap at 3453 ± 39 years BP. The upper regressive overlap occurred at 3285 ± 40 years BP, followed by the upper transgressive overlap at 3198 ± 39 years BP. AMS radiocarbon dates were also obtained from two other cores: BH CA9 and BH CA10. This was done in order to confirm the timings of the regressive and transgressive overlaps recorded in the sample core and to obtain a picture of the pattern of change across the estuary.

5.7 Sea-level change in the Canche Estuary, Northern France

An age-depth plot has been constructed for the Canche (Fig. 5.7) based upon the AMS radiocarbon dates obtained from the regressive and transgressive overlaps in cores BH CA9, CA10 and CA12. The dates showed that the index points represented the mid- to late-Holocene period, and therefore only this period has been included in Fig. 5.7.

Fig. 5.7 shows a curvilinear rise in sea-level over the past 6000 years to the present day. A fairly smooth pattern of sea-level index points, except for one or two outliers can be seen. Application of a sea-level "band" (Long & Innes, 1993) permitted any age and altitude outliers to be allowed for. At the Canche this demonstrates the gradually rising relative sea-level more clearly than simply plotting the sea-level index points.

Stratigraphic position	Core	Lab code	Conventional Radiocarbon Age (years BP +/- 1 σ)	δ $^{13}C_{PDB}$‰ +/- 0.1	Calibrated years (median)	Altitude (m NGF)
Regressive	CA BH12	AA-44092	4720 ±43	-27.6	5329 – 5468 – 5573	+0.45
Transgressive	CA BH12	AA-44093	3453 ± 39	-26.4	3592 – 3692 – 3830	+0.92
Regressive	CA BH12	AA-44094	3285 ± 40	-27.4	3401 – 3508 – 3632	+1.84
Transgressive	CA BH12	AA-44095	3198 ± 39	-27.4	3473 – 3430 - 3354	+2.01
Transgressive	CA BH10	CAMS-78987	2230 ± 40	-27.7	2343 – 2207 - 2123	+4.20
Regressive	CA BH10	CAMS-78988	3670 ± 40	-29.3	4144 – 3982 – 3871	+2.80
Regressive	CA BH9	CAMS-78985	4930 ± 30	-28.0	5724 – 5652 - 5598	+0.64
Transgressive	CA BH9	CAMS-78986	2760 ± 40	-28.5	2950 – 2851 - 2774	+1.72

Table 5.8 A summary of the AMS radiocarbon dates including the stratigraphic position, laboratory code, core number, conventional AMS radiocarbon date, calibrated C^{14} date, carbon content relative to $^{13}C_{PDB}$ ‰ and height of the sample relative to NGF.

The first two dated points both indicate marine regressions, seen by a change in the stratigraphy from silty sand to peat layers, around 4800 radiocarbon years BP (5573-5468-5329 cal. years BP). These regressive overlaps were recorded in both BH CA9 and BH CA12 (4930 ± 30 years BP and 4720 ± 43 years BP respectively), showing a progressively falling relative sea-level. Biostratigraphic data from BH CA12 also shows a progressively falling relative sea-level. At this time tree/shrub pollen replaced Gramineae and Chenopodiaceae, whilst the diatoms showed a shift from marine dominated to brackish dominated and the foraminiferal record showed agglutinated types replaced calcareous types. Since the stratigraphic changes in BH9 and BH12 are believed to represent the same regressive event, the biostratigraphic data from BH12 can be used to support the interpretation of BH9.

The first relative rise in sea-level was shown by a transgressive overlap in the sample core BH CA12, at around 3453 ± 39 years BP (3830-3692-3592 cal. years BP). The stratigraphy showed a shift from silty peat to sandy silt, indicating a increase in relative sea-level. This was supported by the diatom data which was dominated by the tidal flat species *Paralia sulcata* and *Diploneis crabro,* clearly showing a shift from deposition above MHWST to well below, *c.* MTL.

A second fall in relative sea-level occurred *c.* 3285 ± 40 yrs BP (3632-3508-3401 cal. BP), allowing a salt marsh to develop, as recorded in borehole CA12 and supported by the pollen of Gramineae and Chenopodiaceae. Deposition at this time would have been at or around MHWST, producing a reliable sea-level index point.

The pattern of sedimentation was then altered by a second rise in relative sea-level. The effect of this rise was seen first in BH CA12, 3198 ± 39 years BP (3473-3430-3354 cal. years BP) as would be expected due to its position in the estuary and distance from the present day coast.

A third transgressive event was recorded in BH CA9, 2760 ± 40 years BP (2950-2851-2774 cal. years BP). It is thought that the altitude of the transgressive overlap at BH CA9 has been altered resulting from compaction and consolidation of the peat layer by the thick unit of sand and silt that overlies it. If this is the case, then its altitudinal position would be above that of the transgressive overlap in BH CA12, which would be as expected from the dates obtained (refer to compaction section in this chapter).

A final transgressive overlap was seen in BH CA10, 2230 ± 40 years BP (2343-2207-2123 cal. years BP). In order to prove this, foraminiferal and diatom samples were taken from the regressive and transgressive boundaries. No forams or diatoms were recorded in the regressive overlap, with only 2 forams being recorded. However, samples from the upper transgressive overlap did contain diatom tests. Brackish-marine species were present, with *Paralia sulcata*, *Raphoneis amphiceros* and *Nitszchia navicularis* dominant. This was an important result as it provided a sea-level index point at 4.30m NGF. Although this index points provides evidence of a high sea-level, it does not show evidence that sea-level rose above present-day mean high water spring tide (currently 7.18m).

The difference in the altitude of the index points taken from BH10 and those collected from the BH9 and the sample core BH12 (see Fig. 5.7) could be explained by differential sediment compaction. BH10 was situated at the edge of the valley and had a much thinner upper sand layer than the other cores collected at the Canche (see Fig. 5.2), suggesting it had been less influenced by sediment compaction than the other boreholes. BH9 and BH12 both contained about 2m of sand in their upper units, whilst BH10 only contained 0.6m of sand. Therefore, BH10 will have been compacted less than BH9 and BH12. If the sea-level index points taken from BH9 and BH12 were raised then all the sea-level index points would plot in a relatively smooth curve.

The data from the Canche supports all the sea-level index points except the regressive point recorded in BH10 (shaded boxes), which contained no biostratigraphic data to assign an indicative meaning and therefore can not be regarded as a valid sea-level index point. Once again, since the application of the transfer function did not conclusively assign each point to MHWST, the index points plotted on Fig. 5.7 are assumed to represent MHWST and have not been corrected using the assigned tidal levels produced by the diatom-based transfer function.

Potential regional signals are discussed in Chapter Four and Chapter Seven.

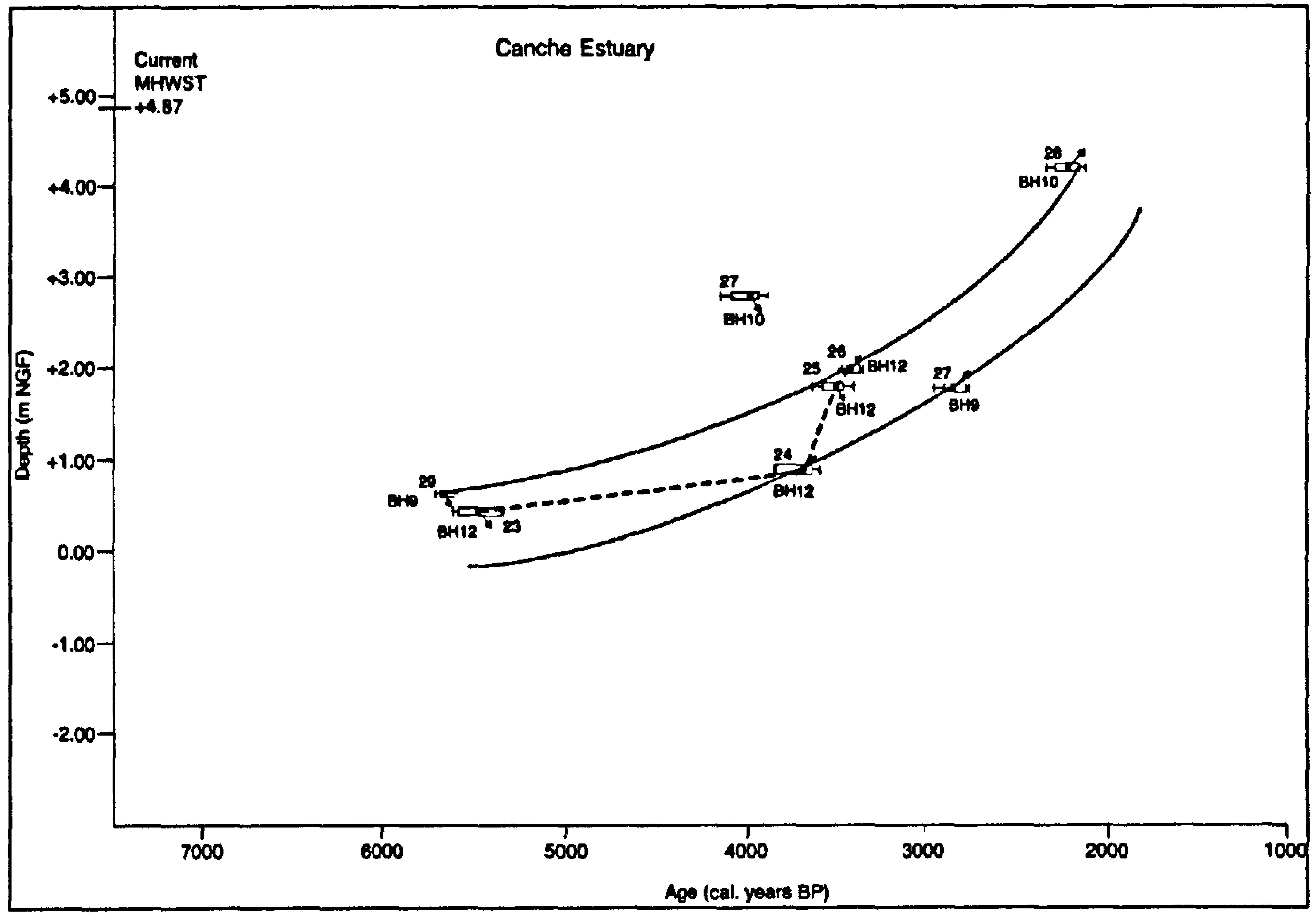


Fig. 5.7 Age-depth plot of sea-level index points and AMS radiocarbon dates obtained from the Canche Estuary, Northern France. The horizontal error bars represents the AMS radiocarbon dating errors (1σ and 2σ). The reference water level for each point is MHWST. The upward arrows represent marine transgressions and the downward arrows represent marine regressions. Shaded boxes indicate that the point is not a valid sea-level index point.

5.8 Estimate of sediment compaction

An estimate of sediment compaction was applied to the sea-level index points obtained from the Canche Estuary using the equation developed by Allen (1999). Empirical bulk densities were taken from the Pevensey Levels and Somme results and all results were found to lie within the ranges expressed by Allen (1999). Once again, detailed results including the calculations may be found in Appendix IV and a summary of the findings is presented in Table 5.9

Sea-level index point (type of overlap)	Original depth (m NGF)	Estimated decompacted depth (m NGF)	Estimate of compaction (m)	Percentage compaction (%)
Sample Core SLIP1 Lower regressive overlap	0.45	0.45	0	0
Sample Core SLIP2 Lower transgressive overlap	0.92	1.146	0.226	24
Sample Core SLIP3 Upper regressive overlap	1.84	2.08	0.30	16
Sample Core SLIP4 Upper transgressive overlap	2.01	2.21	0.20	10
CA BH9 Lower regressive overlap	0.64	0.64	0	0
CA BH9 Upper transgressive overlap	1.73	3.51	1.69	87
CA BH10 Lower regressive overlap	2.80	2.80	0	0

Table 5.9 Summary of the estimates of sediment compaction from the sea-level index points obtained from the Canche Estuary.

The results suggest that significant sediment compaction has taken place at the Canche. The transgressive overlaps revealed the sediment had compacted between 10% and 87%, depending on the thickness of the overburden and the thickness of the peat unit, once more highlighting the considerable effect that sediment compaction has upon sea-level index points. The limitations of the data set and the compaction equation are again apparent, with the lowest regressive overlaps being treated like a basal peat and thus behaving as if they were resting on a non-compactable surface. Unfortunately no data exists to suggest the presence of a basal peat at the Canche, however further research could prove this not to be the case.

The original age-depth data and the decompacted estimates have been plotted together on Fig. 5.8. The corrections made to the sample core cause the curve to lie slightly higher than the original data, as would be expected. The results from CA BH9 showed a smoothly rising pattern of relative sea-level rise. The point was raised by 1.68m clearly demonstrating that sediment compaction must be accounted for if an accurate reconstruction of relative sea-level change is to be made. Once compaction has been estimated and corrected for in all the other cores, the lower date from CA BH10 remained unchanged, showing as an anomaly on the graph. This strengthens the argument that the radiocarbon date is unreliable, causing the point to appear older than it should be.

At the Canche calculating the sediment compaction allowed several of the inconsistencies in the pattern of observed sea-level change to be accounted for. The decompacted data points resulted in a smoother, S-shaped pattern of sea-level curve, exhibiting more similarities to the Somme Estuary, as will be discussed in further detail in Chapter Six.

By allowing for compaction of the sediments using Allen's (1999) equation, the pattern of relative sea-level change at the Canche showed a less fluctuating, rising relative sea-level over the last 6000 years. However, once again the limitations imposed by the data set and the exploratory compaction equation (Allen, 1999) have resulted in a number of shortcomings. Firstly, it was not possible to correct the lower regressive overlaps for sediment compaction. These points needed to be treated as basal peats and therefore had to be assumed to be resting on an incompressible surface. Secondly, the lack of empirical data for compressibility values in the equation for both clay and sand sediments was a particular problem at the French sites, where most cores had at least a metre of sand as the upper stratigraphic unit. If realistic estimates of sediment compaction are to be provided for the Canche, these two limitations must be addressed.

5.9 Conclusion

A smoothly rising sea-level curve has been produced for the Canche Estuary based upon eight sea-level index points. The findings will be compared to previous findings in northern France in Chapter Six, once the results from the Somme Estuary have been presented.

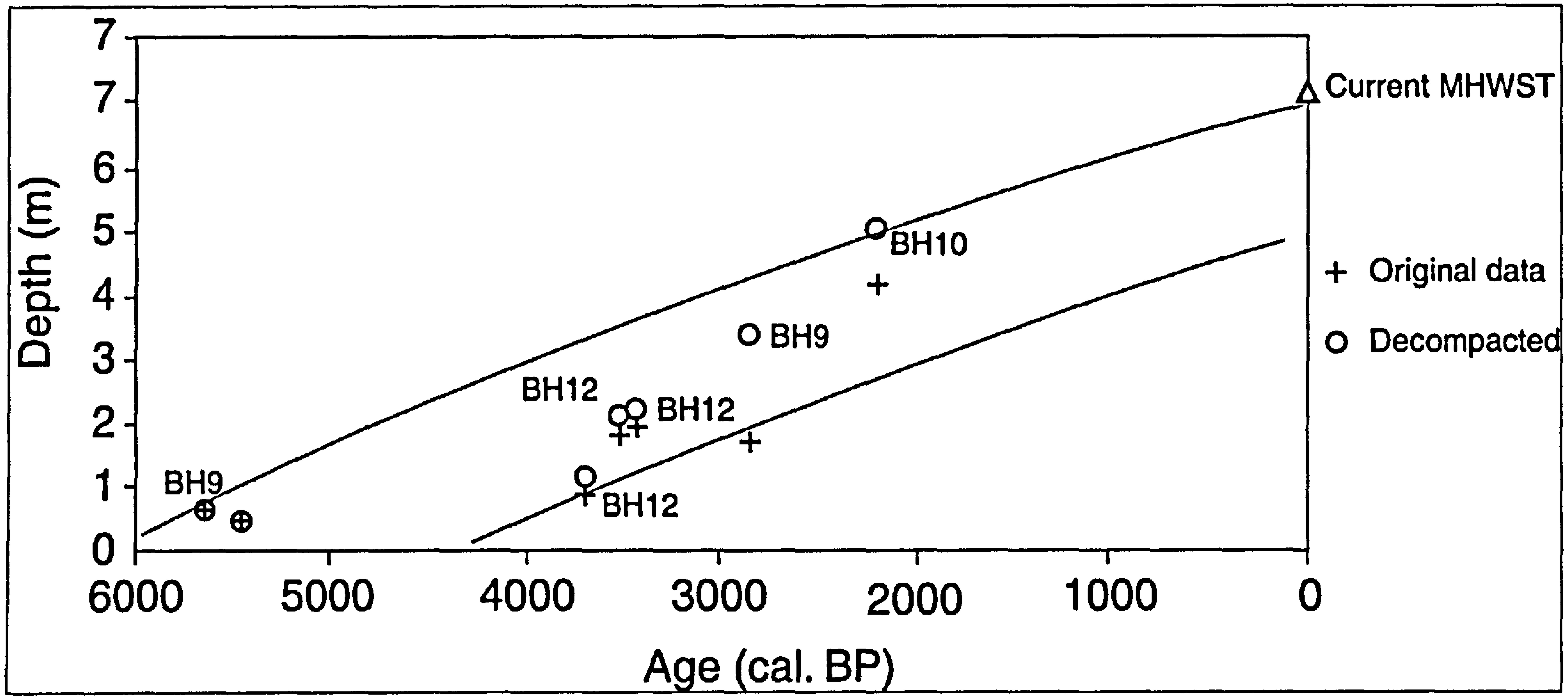


Fig. 5.8 Age-depth plot of original and estimated de-compacted sea-level index points from the Canche Estuary, northern France

Chapter Six Results from the Somme Estuary, N. France

The aim of this chapter is to provide a complete presentation of the results collected from the Somme Estuary. The chapter has been divided into six sections starting with the stratigraphic record, followed by the biostratigraphic record (pollen, diatoms and foraminifera) and a summary of the findings. The chapter then concludes with a discussion of past sea-level changes in the Somme, and compares the findings with other sites in northern France.

6.1 Stratigraphic record

Pre-existing borehole records

The BRGM collected three boreholes from Boismont, near the Somme River (Fig. 3.1). The descriptions were very broad and the detail insufficient to allow any conclusions about the depositional history to be made. Interestingly, no organic layers were recorded, and chalk layers were reached at relatively shallow depths. Table 6.1 provides a summary of the BRGM borehole data.

Borehole No.	Depth	Description
00323X0079/P02	0 – 1.5 1.5 – 26	Silt and chalk White chalk with flints Chalk layer
00323X0082/F-DOM	0 – 1.5 1.5 – 5.8 5.8 – 16 16 – 36 36 – 39	Embankment and silt Sand White chalk Chalk layer White chalk and flints
00323X0083/F-2001	0 – 2.5 2.5 – 5.5 5.5 – 27 10 - 25	Silt Coarse gravel White chalk Chalk layer

Table 6.1 Summary of BRGM borehole data from the Somme Estuary

It can be seen from the data presented in Table 6.1 that sediment layers were simply classified as silt, chalk, sand or coarse gravel. No descriptions of the sediment colour or relative size classes were provided and although considerable depths were attained, the units were too broad to permit a detailed interpretation in terms of sea-level signals.

Stratigraphic data collected from Estréboeuf

The borehole series collected from the Somme area as part of this research was taken from a small valley just to the south of St-Valery-sur-Somme, between Pendé and Estréboeuf (Fig.3.4). Fig. 6.1 presents the stratigraphy of the valley using the Troels-Smith (1955) classification.

The stratigraphic revealed a complex depositional history. The cores taken furthest inland near Pendé (BH SO1, SO2, SO5 and SO6) revealed undifferentiated, poorly-decomposed organic matter, often intercalated by thin silt layers and underlain by gravel or a white sticky sediment, probably a solifluction deposit or weathered bedrock (see BH SO6).

Consistent buried peat layers were not recorded until core SO7 further down the valley (Fig. 3.4 and Fig. 6.1). The lowest unit recorded at SO7 was a well-humified organic deposit. Unfortunately, this unit was difficult to sample. The high water content throughout the peat meant the sample would not remain in the chamber and therefore could not be collected. Unfortunately, no similar organic layers were recovered from the valley. Above this peat layer a horizon of sand and silt was recorded. This sand and silt unit then progressed into a sandy peat unit, which became fully organic just above 0m NGF. Above this, thin layers of sand and organic deposits were recorded across the valley, followed by a sandy peat deposit at +1m NGF and an upper unit of sand with shell remains.

The remaining boreholes all contained layers of intercalated peat, sand and silt (see Fig. 6.1). SO3 was the deepest core obtained from the valley, reaching almost 9m. A blue-grey silt deposit was the deepest unit recorded. Overlying the lowest unit, a blue-grey clay and silt layer with a sand presence was discovered. This clay layer is important as it could signify the presence of shallow calm water, possibly a lagoon. The detrital peat that overlay the clay contained a mixture of wood remains and very well humified organic fragments. A thin layer of blue-grey clay overlay the detrital peat, followed by a second detrital peat. Almost 2m of sand lay above this, followed by a sandy silt layer which became progressively less sandy with height.

Borehole SO8 revealed a sand layer with some silt as its lowest unit, followed by a thin layer of sand, but no sign of the clay layer. The lowest peat layer recovered in BH SO8 was found at approximately 0.07m NGF. The lower peat was overlain by a sandy silt unit, which in turn was overlain by a second peat layer. The upper peat layer was much thinner than the lower peat layer but was less humified and contained some wood remains. Above this a detrital peat progressed into a sand deposit, which continued until a thin silt layer occurred at +1.40m NGF.

Two of the cores collected were perpendicular to the current position of the River Somme (refer to Fig. 3.1), one of which was selected as the sample core (SO9). SO9 was chosen because it contained a high number of potential sea-level index points (see Table 6.2).

Unit	Depth m NGF	Description
SOXI	3.39 – 3.99	**Sand with undifferentiated organic matter** Ga3 Sh1
SOX	3.14 – 3.39	**Silty sandy clay** As2 Ag1 Ga1
SOIX	2.80 – 3.14	**Upper herbaceous peat** Th2 Tl2
SOVIII	2.47 – 2.80	**Sandy peat** Ga2 Dh2
SOVII	1.06 – 2.47	**Detrital peat** Gh3 Dl1
SOVI	0.99 – 1.06	**Transition from sand to detrital peat** Th2 Ga2
SOV	-0.10 - +0.99	**Sand** Ga4
SOIV	-0.40 - -0.10	**Lower woody Peat** Tl3 Ga1
SOIII	-0.80 - -0.40	**Sand** Ga4
SOII	-1.10 - -0.80	**Lower peat** Tl4
SOI	-1.3 - -1.10	**Lower sand** Ga4

Table 6.2 Stratigraphy of the sample core SO9 collected from near Estrébœuf, Somme

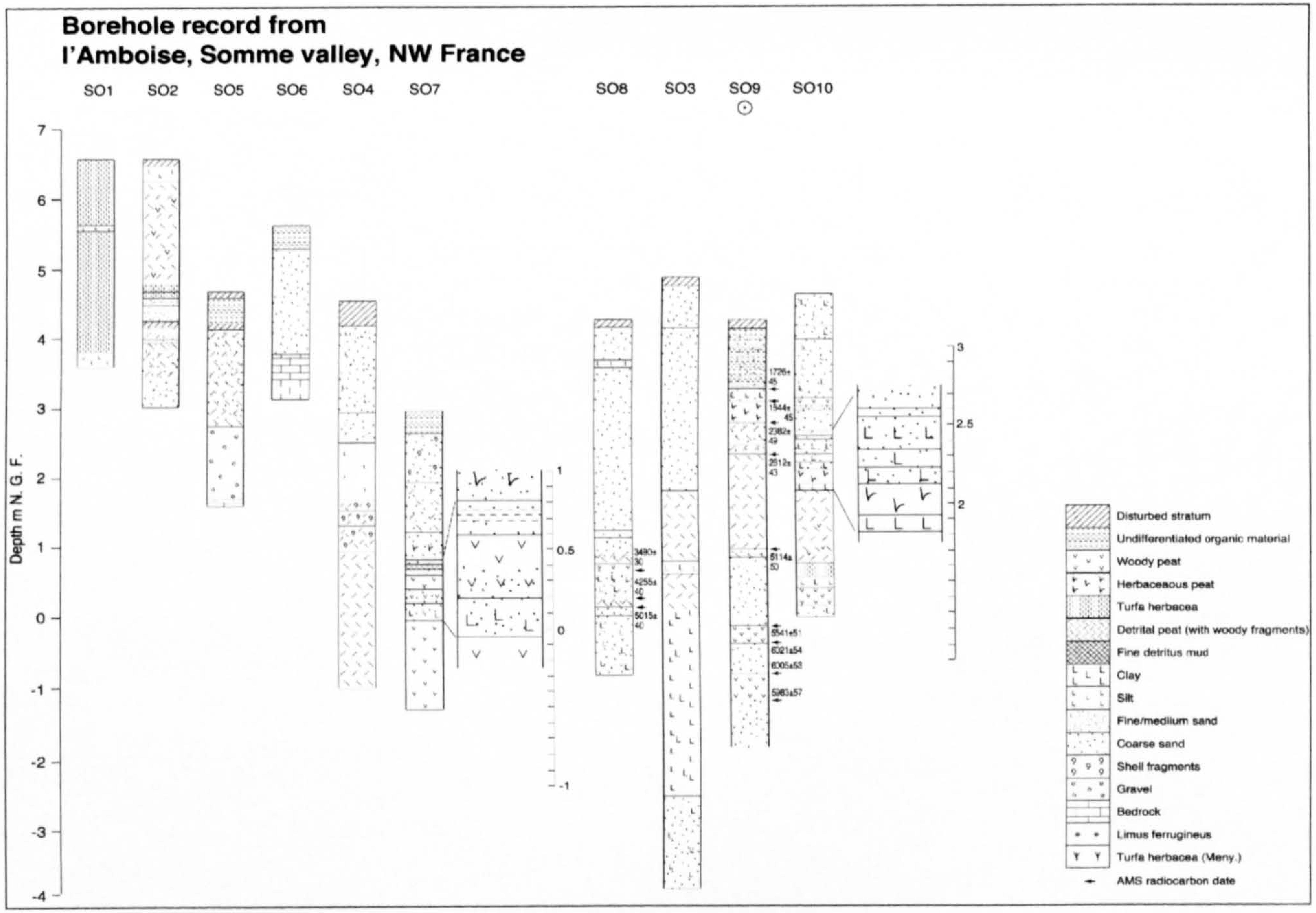


Fig. 6.1 Stratigraphic record from Estrébœuf, Somme Estuary

Symbols represent the Troels-Smith classification (1955)

Unit SOI: Lower sand

The lowest unit recorded in the Somme was a medium grained sand deposit. The nature of the particle size in this deposit suggested that it could have been deposited under turbulent water, indicating it could be marine.

Unit SOII: Lower peat

A thin layer of peat, indicating the first possible marine regressive episode, overlay the sand at the base of the core. The transition was gradual, indicating that the change in sediment deposition took place over a reasonably long period.

Unit SOIII: Sand

The lower peat unit was gradually replaced by a sand unit. This signalled a possible return to marine conditions and the first potential transgressive overlap. The sand was once again grey-blue in colour and fairly coarse.

Unit SOIV: Lower woody peat

The depositional environment was to change once more, with a second peat layer recorded, representing a second potential regressive contact. This transition into this unit was more abrupt than the previous stratigraphic boundaries and the peat contained a higher proportion of wood remains.

Unit SOV: Sand

A second possible transgressive episode is then thought to have taken place, shown by the return of a sand deposition.

Unit SOVI: Transition from sand to detrital peat

A transitional unit containing sand and detrital remains followed. This transitional unit signalled a slowly falling sea-level, the third possible regressive overlap.

Unit SOVII: Detrital peat and Unit SOVIII: Sandy peat

The peat unit which followed contained well-humified plant remains and traces of sand, suggesting that a marine or alluvial influence had remained throughout the deposition.

Unit SOIX: Upper herbaceous peat

These conditions appear to have persisted until this unit SOIX, the upper herbaceous peat, when a relative fall in sea-level must have taken place in order small amounts of wood remains to have been found in the deposit.

Unit SOX: Silty sandy clay

A final potential transgressive overlap, shown by the onset of silty sandy clay, above the herbaceous peat, signalled the possible return to marine conditions, most likely intertidal or a calm water setting, such as a lagoon.

Borehole SO10 also revealed a complex stratigraphy, with the same number of intercalated organic and inorganic units as SO9. Of particular importance was the recovery and replication of the lower organic units. The stratigraphy of the Somme revealed a complex pattern of sediment deposition with many of the up-valley cores (SO1, SO2, SO5 and SO6) possibly being too disturbed to use in a sea-level reconstruction. Further down valley however, the stratigraphy shows frequent changes from organic to minerogenic depositions, providing a number of potential sea-level index points.

6.2 Pollen record

The pollen diagram created for Estréboeuf, the Somme, is described using the stratigraphic boundary units and not local pollen assemblage zones. Fig. 6.2 represents the pollen data graphically and Table 6.3 presents a summary of the main findings for each stratigraphic unit.

Unit SOI: Lower sand (-1.3 - -1.10m NGF)

No pollen samples were taken from this unit due to the inorganic nature of the deposit.

Unit SOII: Lower peat (- 1.10 - - 0.80m NGF)

Gramineae and Chenopodiaceae dominated this unit. The lowest samples showed Chenopodiaceae at 25% and Gramineae at 40% of the total pollen and although values declined slightly, these salt marsh taxa continued to dominate. Total tree pollen increased throughout the unit, beginning at 30% and rising to 50% of the total pollen sum. *Alnus* and *Betula* values increased whilst *Tilia* declined quite dramatically. The occurrence of *Artemesia cf. maritima* indicates the presence of a salt marsh at this time, suggesting that a relative fall in sea-level had taken place. The presence of the wetland species such as *Alnus, Salix* and *Aster*-type suggest the area was still subject to regular flooding. Whether or not this flooding was marine cannot be determined from the pollen record alone.

Unit	Stratigraphy	Biostratigraphy	Depositional Environment
SOXI	Sand with undifferentiated organic matter	Zero count	
SOX	Silty sandy clay	Zero count	
SOIX	Upper herbaceous peat	Gramineae and Chenopodiaceae dominate at start and end of the unit but declined dramatically in the middle leaving tree pollen to dominate	Salt marsh – Woodland – Salt marsh
SOVIII	Sandy peat	Zero count	Inorganic
SOVII	Detrital peat	Gramineae and Tree pollen (up to 80%) including *Betula, Corylus, Tilia* and *Quercus*	Damp deciduous woodland
SOVI	Transition from sand to detrital peat	Low count	
SOV	Sand	Zero count	
SOIV	Lower woody Peat	Gramineae and Chenopodiaceae dominate with *Aster*-type and *Artemesia* plus tree pollen (25%)	Salt marsh
SOIII	Sand	Zero count	
SOII	Lower peat	40% Gramineae 20% Chenopodiaceae plus *Aster*-type present and tree pollen (30-40%)	Salt marsh
SOI	Lower sand	Zero count	

Table 6.3 Summary of the pollen data from Estrébœuf, the Somme Valley

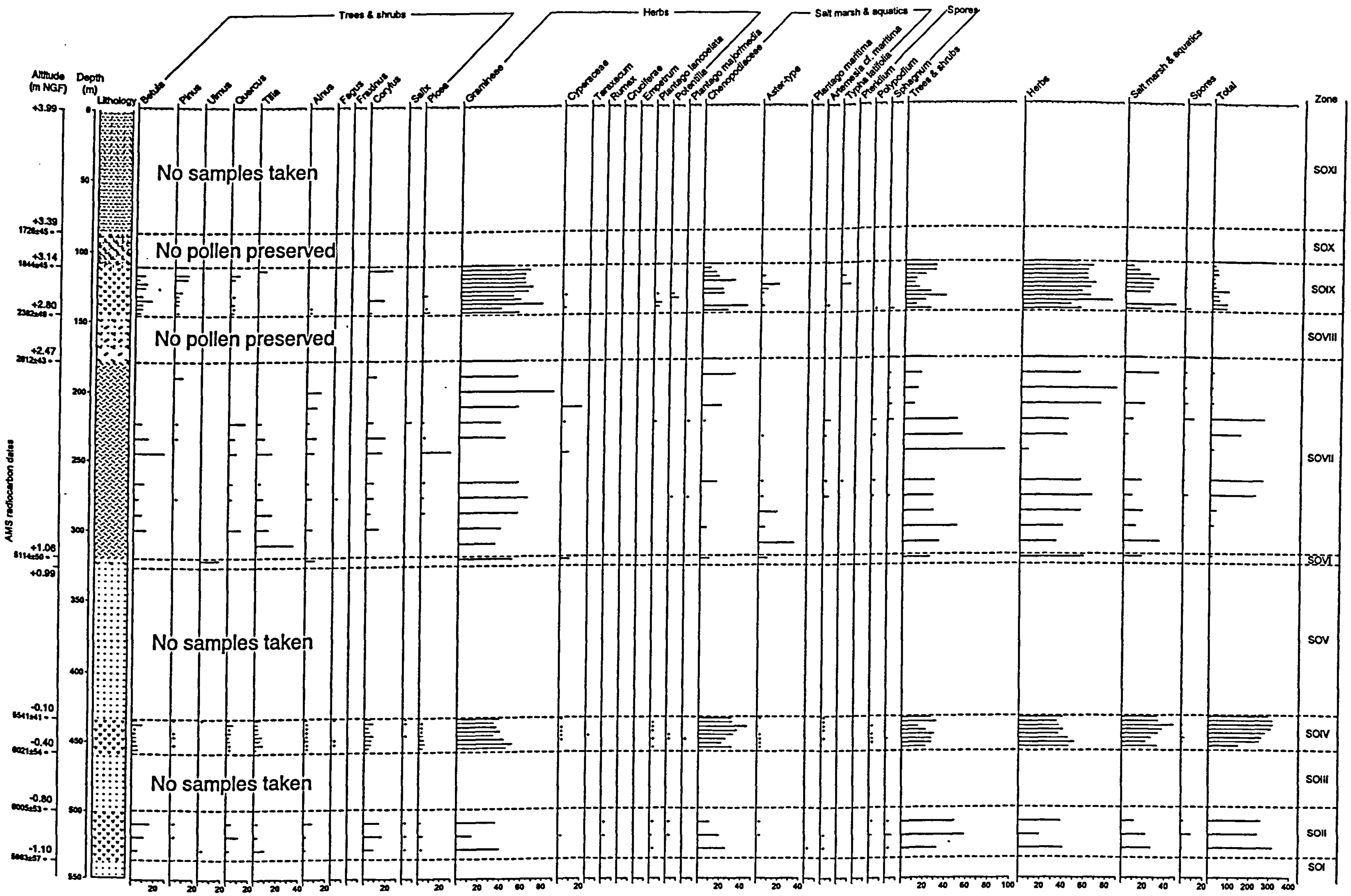


Fig. 6.2 Pollen diagram for Estrébœuf, the Somme Valley

Zones are based upon the stratigraphic boundary divisions and stratigraphic symbols follow the Troels-Smith classification (1955). The data are presented as a percentage of total land pollen and divided into trees, shrubs, herbs, saltmarsh, aquatics and spores.

The end columns present the total values of the pollen data.

Unit SOIII: Sand unit (-0.80 - -0.40m NGF)

Once again no pollen samples were taken from this unit.

Unit SOIV: Peat (-0.40 - -0.10m NGF)

This unit revealed a similar pollen record to the lower peat (unit SOII). Chenopodiaceae and Gramineae dominated, with Chenopodiaceae reaching 45% in the centre of the unit. *Aster*-type and *Artemesia* cf. *maritima*, again suggest the presence of a salt marsh as above, with other open ground taxa such as *Cyperaceae* also confirming that the ground was largely open at this time. Tree and shrub pollen accounted for 30% of the total, with *Betula, Quercus, Tilia* and *Corylus* all present. Levels of *Alnus* were surprisingly low, never exceeding 5% of the pollen count. The close proximity of the valley sides, which would have remained unaffected by any changes in sea-level, probably explains the relatively high levels of tree pollen recorded.

Unit SOV: Sand (-0.10 - +0.99m NGF)

No pollen was sampled from this unit.

Unit SOVI: Transition from sand to detrital peat (0.99 – 1.06m NGF)

The results from this unit produced very low (often less than 50 grains) pollen counts with some Gramineae grains but virtually no Chenopodiaceae. *Cyperaceae* and *Aster*-type indicate open ground environment or possibly a salt marsh, with the presence of *Alnus* tree pollen confirming that the area was damp. However, with the lack of decisive pollen data it is difficult to assign a depositional environment.

Unit SOVII: Detrital peat (1.06 – 2.47m NGF)

Pollen preservation at the onset of this unit was poor. Gramineae, *Aster*-type and tree pollen including *Betula, Corylus* and *Tilia* imply that the site was damp deciduous woodland with a fairly open canopy, with the total tree and shrub percentage between 40 and 60%. Towards the centre of the unit, pollen preservation improved. Gramineae levels rose and the presence of *P. lanceolata, Artemesia* and *Cyperaceae* all indicated open ground or possibly a salt marsh. At 2.45m depth, overall pollen levels fell to almost zero, possibly indicating a period of drying out, but recovered again. Towards the top of the unit however, a major shift in the pollen can be seen with the introduction of Chenopodiaceae, suggesting that either marine or brackish conditions encroached the site.

Unit SOVIII: Sandy peat (2.47 – 2.80m NGF)

No pollen was preserved in this unit.

Unit SOIX: Upper herbaceous peat (2.80 – 3.14m NGF)

Gramineae and Chenopodiaceae dominated throughout this unit, except for between 1.29m and 1.26m depth, where pollen preservation declined, which could indicate a period of severe drying out. No evidence existed in the stratigraphic record to suggest this latter theory, but the presence of damaged pollen grains suggested that the sediment probably dried out. In the lower samples *P. lanceolata* and *Sinapis*-type, both potential indicators of human activity, were present, but fail to return after the break in pollen preservation. However, *Typha latifolia* does appear after the 1.29m depth indicating the presence of a water body nearby. Tree pollen remains fairly constant, with *Betula, Quercus* and *Pinus* all present throughout the unit, once again signifying the close proximity of dry valley sides. Salt marsh conditions would have prevailed throughout much of this phase, with daily marine inundation at high tide.

Unit SOX: Sandy silty clay (3.14 – 3.39m NGF)

Only a single sample was obtained from the contact, which showed salt marsh taxa continuing to dominate. No pollen was recorded from the remainder of this unit.

Unit SOXI: Sand with undifferentiated organic matter (3.39 – 3.99m NGF)

No pollen samples were taken from this unit because the sediment appeared to be quite disturbed, containing flints and coarse-grained sands.

Summary of pollen data

The pollen from the two lower peat units, SOII and SOIV, suggested that a salt marsh was present at the time of sediment deposition. The stratigraphy points toward the presence of two regressive and two transgressive overlaps in the lower sediments. However, confirming this without other palaeoecological indictors is not possible. It is not until unit SOVI that the pollen record becomes sufficient to begin to determine the pattern of sea-level change. A more gradual decline in sea-level can be suggested by the transitional unit containing sand and detrital peat and a further relative fall was marked by the detrital peat containing Gramineae and tree pollen, up to 80% of the total count. The onset of unit SOVIII, a sandy peat, perhaps signalling the return of marine conditions, but unfortunately no pollen was preserved. The upper herbaceous peat (unit SOIX) marks the largest relative fall in sea-level at the Somme, with pollen revealing a distinct salt marsh, to woodland, and back to salt marsh evolution. It is believed there was also a severe dry period, shown midway through this unit by a sharp decline in total pollen. The final relative rise in sea-level can then be seen by the return to silty sandy clay, although no pollen was preserved throughout units SOX and SOXI.

6.3 Diatom data

As in the previous sections, the palaeoecological data has been constrained by the stratigraphic units. This has been done to aid the comparison between indicators and sites. Fig. 6.3 presents the diatom diagram for the sample core and Table 6.4 provides a summary of the main findings.

Unit	Stratigraphy	Biostratigraphy	Depositional Environment
SOXI	Sand with undifferentiated organic matter	Zero count	
SOX	Sandy silty clay	*R. amphiceros, P. sulcata, P. westii*	Marine/Brackish - salt marsh
SOIX	Upper herbaceous peat	*P. sulcata* and *P. westii*	Marine/Brackish - salt marsh
SOVIII	Sandy peat	*D. crabro* and *A. delicatula* plus other brackish species	Brackish/Marine - tidal flats
SOVII	Detrital peat	No samples taken	Terrestrial
SOVI	Transition from sand to detrital peat	Low counts	
SOV	Sand	Lowest few levels contained *A. delicatula* Zero counts throughout	Brackish/Marine - tidal flats
SOIV	Lower woody Peat	*R. amphiceros, P. sulcata* and *P. westii* dominate	Brackish/marine - salt marsh with channel inlets
SOIII	Sand	Zero counts	
SOII	Lower peat	Zero counts – *P. westii* and *P. sulcata* appear towards the end of the unit	Marine/Brackish - salt marsh
SOI	Lower sand	*R. amphiceros, N. navicularis* and *O. schwartzii* present in high numbers but dominated by *P. sulcata* and *P. westii*	Marine - tidal flats

Table 6.4 Summary of findings for each stratigraphic unit

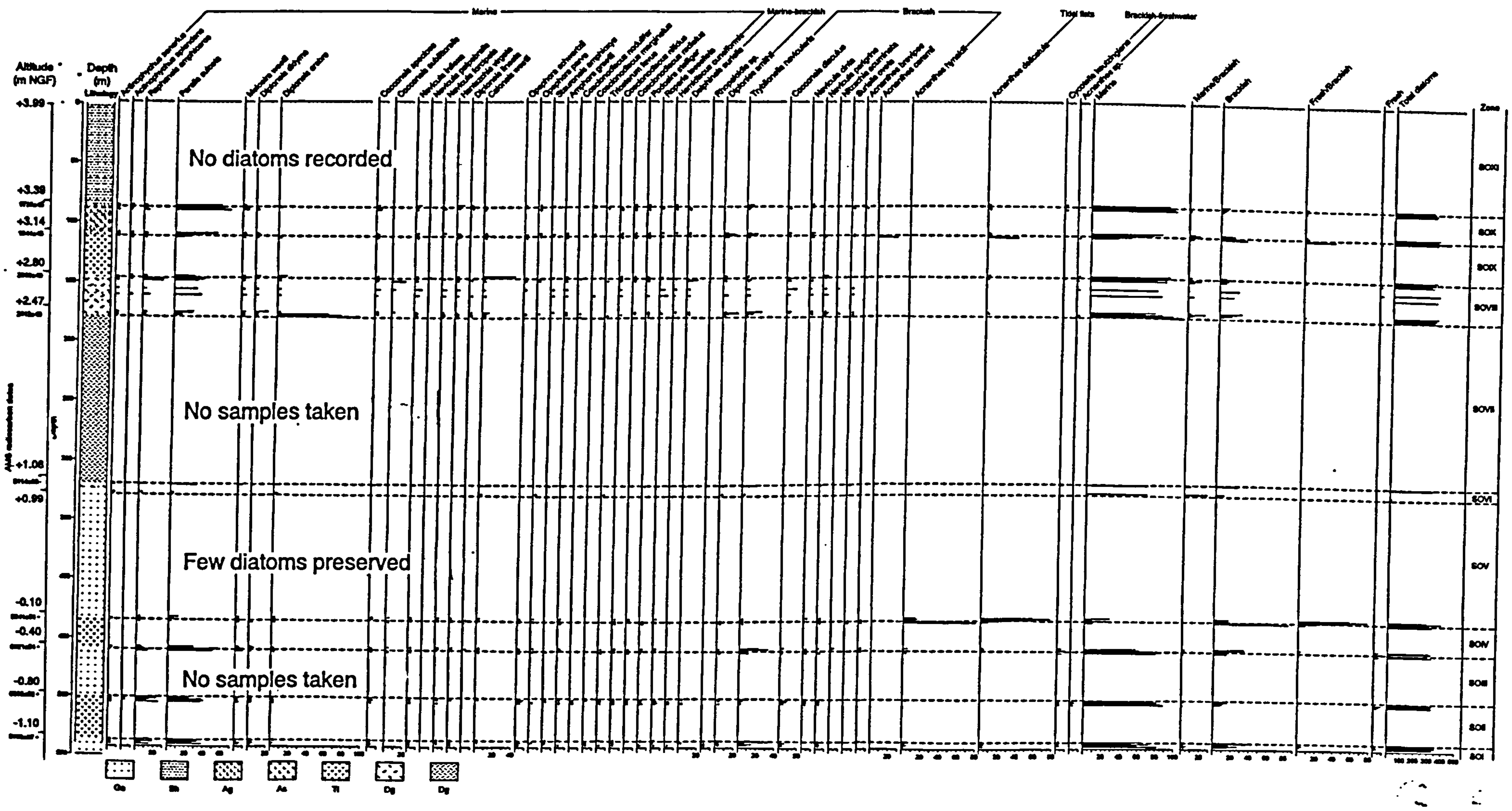


Fig. 6.3 Diatom data for the Somme

Zones are based upon the stratigraphic boundary divisions and stratigraphic symbols follow the Troels-Smith classification (1955). The data are presented as a percentage of total diatoms and is divided into marine, marine-brackish, brackish, tidal flats and freshwater.

Unit SOI: Lower sand (-1.30 - - 1.10m NGF)

The diatom record for this unit revealed high proportions of marine diatom species, dominated by *Raphoneis amphiceros,* a polyhalobous tidal inlet species commonly found on the English Channel coast (Hendey, 1964) and *Paralia sulcata,* a polyhalobous tidal flat species. *Opephora schwartzii, Nitzschia navicularis* and *Diploneis didyma,* all marine-brackish or brackish dwelling species, were also present throughout the unit. This unit most likely represents a sand flat deposit, with the presence of *P. sulcata* and *Psuedopodosira westii* towards the top of the unit indicating a transition into salt marsh deposition (unit SOII).

Unit SOII: Lower peat (- 1.10 - - 0.80 m NGF)

No diatoms were found in the lower samples from this unit, a common problem in purely organic sediments. However, towards the top of the layer *P.sulcata* and *P. westii* appeared again, suggesting that the upper part of the unit is either indicative of a salt marsh deposit or that marine washing of the peat has taken place. Many other marine diatoms were also found, the presence of *R. amphiceros* for example, showing either frequent marine inundation or the presence of tidal channels.

Unit SOIII: Sand unit (- 0.80 - - 0.40m NGF)

The sediment collected was a blue-grey silty sand. Only a single diatom sample was taken from this unit, at the very top, and it was decided that the foraminifera would provide more conclusive findings.

Unit SOIV: Lower woody peat (- 0.40 - - 0.10m NGF)

Samples were taken from around the lower and upper stratigraphic contacts. The lower samples showed the presence of salt marsh and tidal channel species, with *R. amphiceros, P. sulcata* and *P. westii* present. In addition to this *Tryblionella navicularis* was present. This is an epipelic species, which favours brackish water and is frequently recorded in the intertidal zone or in creeks, marine basins or lagoons (Zong & Horton, 1998). Towards the top of this unit, the tidal flat species *A. delicatula* values rose, continuing into the sand deposit, indicating a relative rise in sea-level.

Unit SOV: Sand (-0.10 – 0.99m NGF)

No diatoms were preserved in this unit except in the lowest few levels, which showed dominance by *A. delicatula*, indicating sandy tidal flats, the presence of which suggests it was either an estuarine deposit or an intercalated sandflat.

Unit SOVI: Transition from sand to detrital peat (0.99 – 1.06m NGF)

Diatom preservation was poor throughout this deposit. Marine diatoms were present but in low numbers, making it difficult to assign an indicative meaning.

Unit SOVII: Detrital peat (1.06 – 2.47m NGF)

No diatom samples were taken from this unit due to the organic nature of the sediment.

Unit SOVIII: Sandy peat (2.47 – 2.80m NGF)

Diploneis crabro dominated the early levels of this unit showing a highly saline environment, but declined and then disappeared quickly. Many other marine and brackish species were also present most of which are indicators of the tidal flat zone. *A. delicatula* was present but not in significant quantities and the brackish species The occurrence of *Cocconeis disculus* also rose, suggesting brackish, intertidal conditions. The high presence of *Diploneis smithii* recorded for the first time in this deposit, confirms this.

Unit SOIX: Upper herbaceous peat (2.80 – 3.14m NGF)

Samples were collected from the sediments surrounding the lower and upper contacts. The lower contact with the sandy peat (unit SOVIII) showed the presence of *R. amphiceros*, *P. sulcata*, *P. westii* and *Caloneis westii*, for the first time in considerable quantities. These species are frequently recorded on muddy tidal flat deposits, and it is possible that here they represent the beginnings of a salt marsh deposit. The shift from a highly saline environment in unit SOIX to an herbaceous peat indicates a relative fall in sea-level took place.

Towards the upper contact the tidal flat species *A. delicatula* returned. However, this was a short-lived appearance as the percentage of *Acnanthes delicatula* fell quickly as the sediment became sandier toward the contact with the overlying sandy silty clay, possibly showing a return to fully marine conditions.

Unit SOX: Sandy silty clay (3.14 – 3.39m NGF)

Marine species can be seen to dominate this unit. *R. amphiceros, P. sulcata, P. westii* and the marine-brackish species *Diploneis smithii* all appeared in large numbers. *N. navicularis*, a brackish water species, was also present. Evidence suggests that the area was under a marine influence again. A strong tidal influence could possibly have allowed a mixture of marine and brackish species to exist and *P. sulcata* is perhaps over-represented, being washed into environments it would not normally inhabit.

Unit SOXI: Sand with undifferentiated organic matter (3.39 – 3.99m NGF)

No diatoms were recorded from this unit.

Summary of diatom data

The lowest unit was dominated by fully marine diatom species indicating that the sea covered the area at this time. A relative sea-level fall must have then taken place, shown by the onset of the lower peat deposit. Whether or not the sand unit above this was laid down under marine conditions could not be determined from the diatom record alone. The second relative fall was marked by the development of the peat layer (unit SOIV), which the diatom record indicated was a salt marsh deposit. A slight rise in sea-level can then be seen to occur towards the sand unit (SOV) above this, marked by the presence of the tidal flat species *A. delicatula*. Units SOVI and SOVII contained too few diatoms to draw any conclusions about the depositional environment. A fall in sea-level can then be seen in unit SOVIII when conditions were seen to become more brackish. The final rise in sea-level occurred as the sediment became more sandy and marine diatoms dominated.

Diatom-based transfer function

As at Pevensey and the Canche, in order to validate the diatom data presented above and reconstruct palaeo-tidal level, the results were calibrated using a diatom-based tidal level transfer function (Zong & Horton, 1998, 1999). Full details of the calibration dataset that was used are contained in Chapter Three. The transfer function was then applied to the fossil data collected from the Somme Estuary providing the results detailed in Table 6.5 and Fig. 6.4, where MHWST has a SWLI of 300. In order establish the altitude of the sample relative to OD, the SWLI were back-transformed using local MHWST and MTL (see Equation 4.1)

All the samples fell between MHWST (SWLI of 300) and MTL (SWLI of 200), with no samples above MHWST. The results have perhaps again been distorted by the imbalance of species that were present and those in the training set, with only 15 of the 24 taxa present in the fossil data set being present in the DBTF training set.

The data appeared to show that the results obtained from the transgressive overlaps performed more reliably than those obtained from regressive overlaps, as at Pevensey and the Canche. However, at the transgressive overlap at 437cm depth (-0.10m NGF) the DBTF performed particularly poorly, showing a reconstructed SWLI of 220, just above MTL. Of the 12 species recorded in the fossil record, only 7 were present in the training set, only 58%. The diatoms recorded from this sample revealed dominance by the brackish species *Acnanthes haynaldii*, which is not present in the training set. Thus, the remaining species such as *Acnanthes delicatula* appeared to dominate the sample, thus placing the reference tidal point at MHWST-2.98m, much lower than it actually should have been, based on the known tolerances of the diatoms recorded.

The regressive overlap at +1.06m NGF (320cm depth) did not contain any diatom species. However, the sample from 319cm was assigned a tidal depth of MHWST-1.89m. This is one of the more reliable results obtained, since it appeared to closely correspond to the tidal level suggested by the diatoms. Although only 12 out of the 21 species present in the training set, these included the most dominant species such as *P. sulcata*. Unfortunately, though several freshwater species (*Surirella ovata* and *Acnanthes sp.*) were recorded at this depth, which would have resulted in deposition closer to MHWST, had these species been present in the training set.

The transgressive overlap at +2.42m NGF (184cm depth) once again did not contain any diatoms; however at 179cm depth palaeo-tidal level was placed at MHWST -1.29m. Only 6 out of 11 fossil species were present in the training set, however this result is probably reliable. The presence of *Diploneis crabro*, although not in the transfer function, and *P. sulcata* suggest marine-brackish conditions prevailed at this time, possibly even the presence of a salt marsh, which the transfer function predicted reasonably well.

Depth	SWLI	Back-transformed depth	Reference Water Levels (MHWST +/-)
85.5	237	2.72	-3.05
86.5	239	2.80	-2.97
87.5	239	2.80	-2.97
88.5	242	2.97	-2.80
89.5	241	2.89	-2.88
108.5	259	3.76	-2.01
109.5	266	4.14	-1.63
110.5	272	4.39	-1.38
111.5	255	3.61	-2.16
112.5	251	3.39	-2.38
144.5	266	4.12	-1.65
145.5	262	3.94	-1.83
146.5	247	3.19	-2.58
147.5	252	3.43	-2.34
148.5	234	2.58	-3.19
155.5	244	3.04	-2.73
160.5	259	3.79	-1.98
174.5	259	3.76	-2.01
175.5	276	4.60	-1.17
176.5	274	4.50	-1.27
177.5	263	3.96	-1.81
178.5	273	4.48	-1.29
319.5	261	3.88	-1.89
431.5	226	2.16	-3.61
432.5	223	2.01	-3.76
433.5	230	2.35	-3.42
434.5	239	2.80	-2.97
435.5	238	2.79	-2.98
456.5	251	3.39	-2.38
457.5	254	3.54	-2.23
459.5	243	3.00	-2.77
460.5	244	3.08	-2.69
500.5	250	3.36	-2.41
501.5	246	3.17	-2.60
502.5	239	2.82	-2.95
503.5	243	3.01	-2.76
504.5	243	3.02	-2.75
536.5	253	3.51	-2.26
537.5	253	3.50	-2.27
538.5	243	3.02	-2.75
539.5	258	3.72	-2.05
540.5	240	2.86	-2.91

Table 6.5 Transfer function data from the Somme Estuary

SWLI refers to standardised water level index

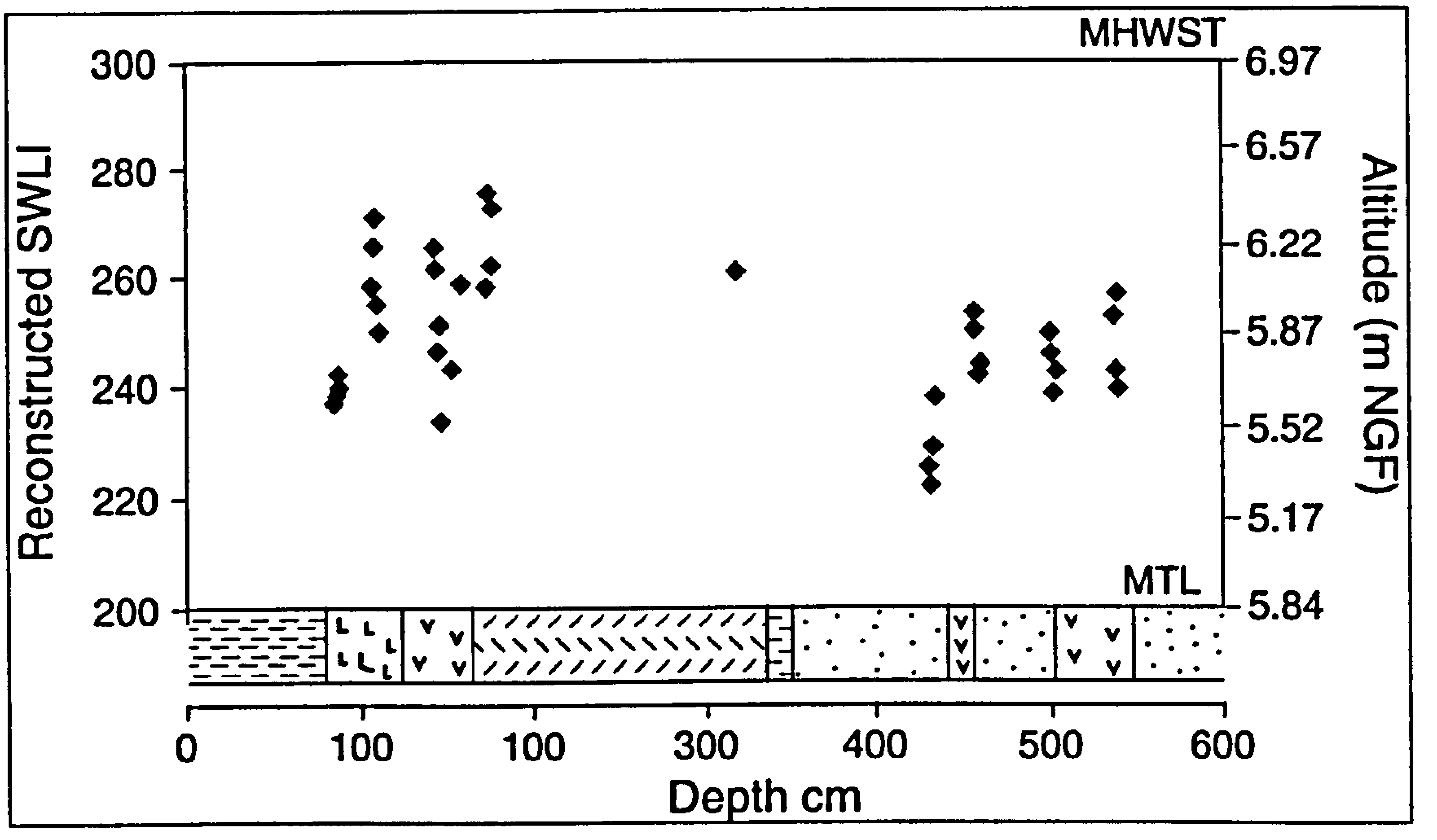


Fig. 6.4 Reconstructed standardised water level index for the Somme Estuary

The regressive overlap at +3.15m NGF (111cm depth) once again should have placed the sample closer to MHWST. Only 13 of the 20 species were present in the training set. Although many of the freshwater species were present in the training set, *Navicula peregrina* for example. However, the high presence of *Paralia sulcata* and *A. delicatula*, associated with tidal flats and altitudes near MTL, could have caused the transfer function to reconstruct palaeo-tidal level below what it should have been.

The final transgressive overlap at +3.39m NGF (87cm depth) produced a palaeo-tidal level of MHWST - 2.97m due to the high presence of *P. sulcata* and *A. delicatula*. Only 8 of the 14 species present in the fossil data set were in the DBTF training set. However, because the two dominant species recorded in the fossil data set were present in the training set, the DBTF appears to have worked reasonably well. However, as discussed in Chapter Five, this could cast doubt on previous interpretations based on stratigraphic and biostratigraphic data (refer to p.177).

The results from the Somme performed in a similar way to the results obtained from the Canche. Important marine species such as *Diploneis crabro* and *Pseudopodosira westiii* and freshwater species such *Acnanthes hynaldii* and *Cyclotella keutzighiana* were absent from the training set. The transgressive overlaps appeared to perform marginally better than the regressive overlap, due to the species such as *P. sulcata* recorded at these shifts. However, improvements to the training set are required to improve the quality of results from regressive overlaps.

6.4 Foraminifera data

Descriptions are based upon stratigraphic divisions and not independent foraminiferal assemblage zones. Fig. 6.5 presents the foraminiferal diagram and Table 6.6 provides a summary of the main findings for each stratigraphic unit.

Unit	Stratigraphy	Biostratigraphy	Depositional Environment
SOXI	Sand with undifferentiated organic matter	*Elphidium williamsonii* and *Ammonia beccarii* present but in very low numbers	
SOX	Sandy silty clay	Calcareous dominate *A. beccarii*	Brackish/Marine - lagoon/estuary or mudflats
SOIX	Upper herbaceous peat	Calcareous *A. beccarii. E. williamsonii* & *N. depressulus*	Brackish/marine - lagoon or mud flats
SOVIII	Sandy peat	*E. williamsonii* and *A.beccarii* dominant with the presence of *N. depressulus* and *Rosalina* sp.	Brackish – marine – low marsh or tidal flats
SOVII	Detrital peat	Upper contact: calcareous species	Brackish/Marine - lagoon
SOVI	Transition from sand to detrital peat	None	
SOV	Sand	None	
SOIV	Lower woody Peat	Upper contact *J. macrescens* appeared in low numbers plus *Rosalina* sp.	Marine/Brackish - salt marsh
SOIII	Sand	Few *T. inflata* & *A. beccarii*	Marine – tidal flats
SOII	Lower peat	None	
SOI	Lower sand	One or two *A. beccarii* tests	Marine – tidal flats

Table 6.5 Summary of foraminiferal data for each stratigraphic unit

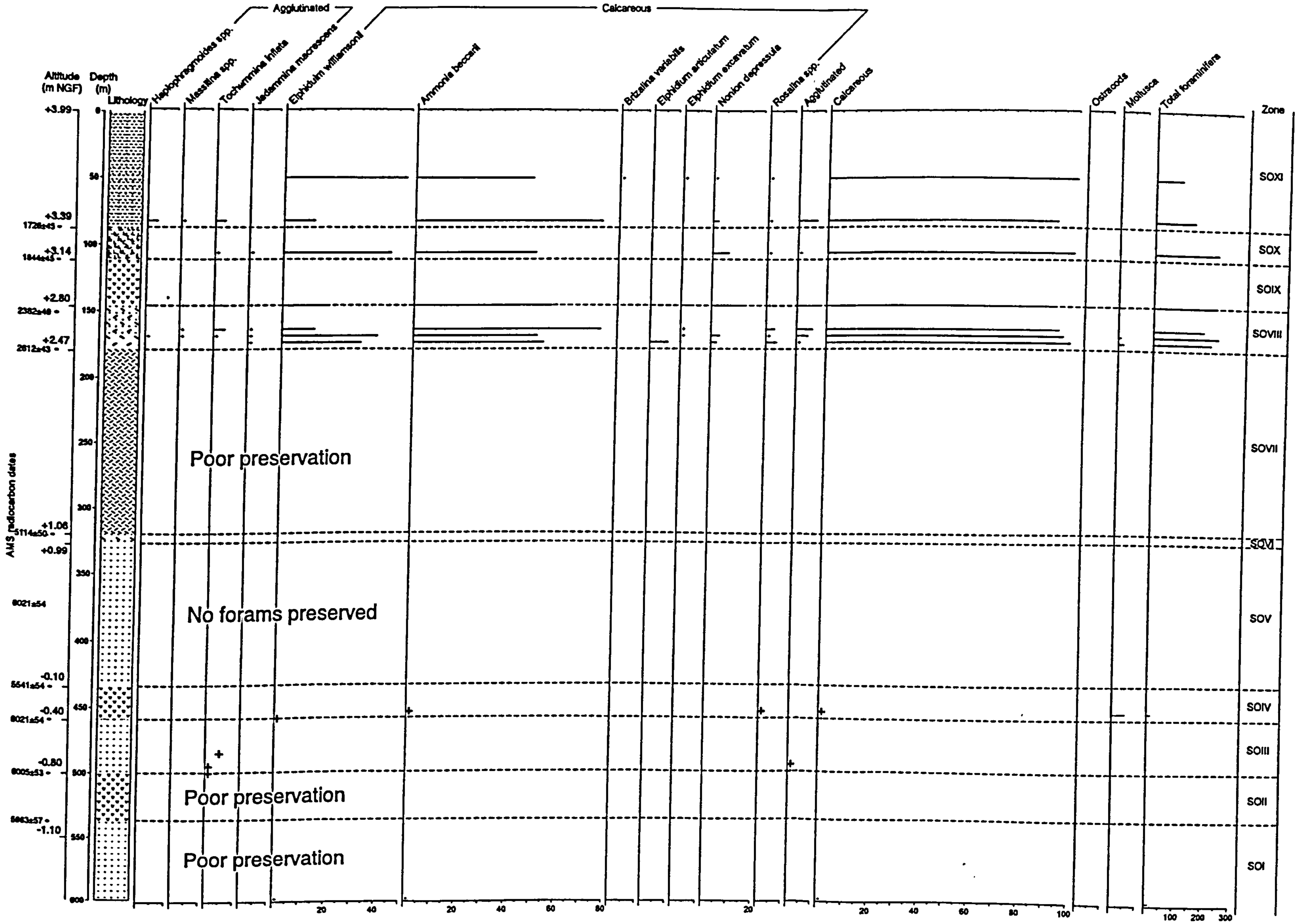


Fig. 6.6 Diagram of foraminiferal data

Zones are based upon the stratigraphic boundary divisions and stratigraphic symbols follow the Troels-Smith classification (1955). The data are presented as a percentage of total foraminifera and divided into agglutinated and calcareous species.

Preservation varied greatly between the units, with many of the lower units failing to provide adequate tests to counts. Units SOI to SOVII contained very few foraminifera, with more being observed in units SOVIII to SOXI. The reasons behind this are not fully known. The diatom record suggested that the sands were marine deposits and it is therefore unexpected that there would be so few foraminifera present.

Unit SOI: Lower sand (-1.30 - -1.10m NGF)

Preservation of the tests was low in this unit. At one level only 25 tests of *Ammonia beccarii* were recorded indicating that tidal flats may have dominated the site at this time. However, it was not possible to draw any conclusions due to the insufficient record.

Unit SOII: Lower peat (-1.10 - -0.80m NGF)

No foraminifera were present throughout this layer until the stratigraphic boundary with SOIII and even then tests were sparse, with only two *Trochammina inflata* tests observed. *T. inflata* is normally observed between MHW and MHWST.

Unit SOIII: Sand (-0.80 - -0.40m NGF)

Again, only *T. inflata* was recorded near the lower stratigraphic contact, suggesting a similar tidal level to the previous unit (SOII). However, it must be noted that dead tests are often found outside of their natural habitat in near by lagoons or nearshore environments, having been washed in by tides.

Unit SOIV: Peat (-0.40 - -0.10m NGF)

Only a few foraminifera were preserved in this unit, mainly *Ammonia beccarii*, indicating that this unit represents tidal flats or possibly even a low marsh depositional environment. *A. beccarii* is commonly recorded between MHWST and MHWNT on English Channel coasts (Haslett, 1997). Unfortunately, it is difficult to assign a definite depositional environment to this unit due to the shortage of foraminiferal data.

Unit SOV: Sand (-0.10 – 0.99m NGF)

Several samples were taken from this unit, none of which contained any fossil data.

Unit SOVI: Transition from sand to detrital peat (0.99 – 1.06m NGF)

Once again the sample from this unit did not contain any foraminiferal test remains.

Unit SOVII: Detrital peat (1.06 – 2.47m NGF)

Only a single sample from this unit contained fossil data and that was at the upper stratigraphic boundary. *J. macresecens* was recorded, albeit in very low quantities, suggesting a salt marsh deposit since this species is found at HAT or in low marsh sediments (Haslett, 1998).

Unit SOVIII: Sandy peat (2.47 – 2.80m NGF)

This unit contained the first good foraminiferal record for the site. *Elphidium williamsonii* and *Ammonia beccarii* dominated the counts and *J. macresecens* was present, indicating that it was a salt marsh at this time. These species are all associated with low marsh or tidal flat environments and are found at altitudes between MHWST and MHWNT (Haslett, 1998). Several other calcareous species such as *Nonion depressulus* were also recorded, suggesting the area was regularly flooded during high tides.

Unit SOIX: Upper herbaceous peat (2.80 – 3.14m NGF)

No foraminiferal tests were recovered from this unit, probably a result of the fall in sea-level recorded by the pollen and diatom data.

Unit SOX: Sandy silty clay (3.14 – 3.39m NGF)

Calcareous species dominated this unit with *E. williamsonii, A. beccarii* and *N. depressulus* all present in high percentages. These calcareous types again suggest a tidal flat or low marsh depositional environment, with the area flooded regularly at high tide. The presence of *J. macresecens* points towards the sediment being a salt marsh deposit. It is therefore likely that relative sea-level had risen during this stage, but brackish conditions continued to prevail.

Unit SOXI: Sand with undifferentiated organic matter (3.39 – 3.99m NGF)

E. williamsonii and *A. beccarii* continued to dominate into this unit. However, several agglutinated species were also recorded. The presence of *Haplophragmoides* sp. *Massilina* sp. and *Elphidium excavatum* suggest that either the deposit has been re-worked, since these species are associated with deep water or inner shelf habitats, or that the deposit was storm derived. The origin of this deposit is therefore unknown.

Summary of the foraminiferal data

The foraminiferal data from unit SOI, the lowest unit, indicated that the area was under marine influence at the time of sediment deposition. A fall in sea-level appears to have taken place shown by the onset of the lower peat, although with a lack of foraminiferal evidence supporting this. The presence of salt marsh foraminifera in unit SOIII suggests a return to more marine conditions, with the area being regularly flooded. Unit SOIV, the sand unit above this did not contain many forams, making determining the origin impossible. The fact that few foraminifera were preserved strengthens the suggestion that the area was not under a marine influence. The presence of sand in unit SOVIII, should have allowed a foraminiferal record to be obtained, however no forams were recorded. The return of organic sediments in Unit SOIX points toward a relative fall in sea-level, but this unit did not contain any foraminifera. The final rise was shown by the sandy silty clay unit (SOX), which contained calcareous foraminifera, suggesting it was laid down in a lagoon or on estuarine mud flats. The low concentration of foraminifera makes assigning a depositional environment difficult. However, many authors have used very low counts to reconstruct past sea-levels (Haslett *et al.* 1998) and thus tentative interpretations have been attempted here.

6.5 Summary of palaeo-ecological data and sea-level interpretation

The above discussion provides detailed information about the findings of each indicator. However, no single indicator provided a full record for all the different stratigraphic units involved. Fig. 6.6 provides a graphical summary of the pollen, diatoms and foraminifera, dividing each into their main habitat classifications.

Unit SOI: Lower sand ($^-$1.30 - $^-$1.10m NGF)

The diatom data from this unit suggested that a tidal flat environment existed at this time, with tidal level at or around MTL. It was hoped that the foraminiferal data would support this proposal but unfortunately no foram tests were preserved in the sediment. Fossil pollen was also absent from this unit, but that would be expected. However, it is believed that the sediments recorded here represent deposition under a marine/brackish environment.

Unit	Stratigraphy	Biostratigraphy	Depositional Environment
SOXI	Sand with undifferentiated organic matter	No pollen, diatoms or foraminfiera recovered	Inorganic
SOX	Silty sandy clay	No pollen preserved. Marine diatoms dominated by *R. amphiceros*, *P. sulcata* & *P. westii*. Calcareous foraminifera species *A. beccarii* dominated	Salt marsh or mud flats
SOIX	Upper herbaceous peat	Gramineae and Chenopodiaceae dominate at start and end of the unit but decline dramtically in the middle leaving tree pollen to dominate. *P sulcata* and *P. westii* dominated the diatom record and calcareous foraminifera were present	Salt marsh – Woodland – Salt marsh
SOVIII	Sandy peat	No pollen or foraminifera were preserved. Brackish diatoms were present in adequate numbers	Brackish Tidal flats
SOVII	Detrital peat	Gramineae and Tree pollen (up to 80%) including *Betula*, *Corylus*, *Tilia* and *Quercus*. No diatoms were sampled and a few calcareous foraminifera were recovered	Damp deciduous woodland
SOVI	Transition from sand to detrital peat	Low counts of pollen, diatoms and foraminifera	Unknown
SOV	Sand	No pollen or foraminifera were preserved. A few *A. delicatula* were recovered	Tidal flats or a fluvial deposit
SOIV	Lower woody Peat	Gramineae and Chenopodiaceae dominated with Aster-type and *Artemesia*. Marine diatoms species were present in high percentages. No foraminifera were present except for *J. macrescens* at the upper contact	Salt marsh with tidal channels and inlets
SOIII	Sand	No pollen or diatoms were preserved. Low occurrences of *T. inflata* & *A. beccarrii*	Marine Tidal flats
SOII	Lower peat	Gramineae & Chenopodiaceae plus Aster-type present with low counts of marine diatoms. No foraminifera were preserved	Salt marsh
SOI	Lower sand	No pollen was preserved. Marine diatom species were present in high numbers. A few *A. beccarii* were present	Marine salt marsh / tidal flats

Table 6.7 Summary of palaeoecological data from Estrébœuf

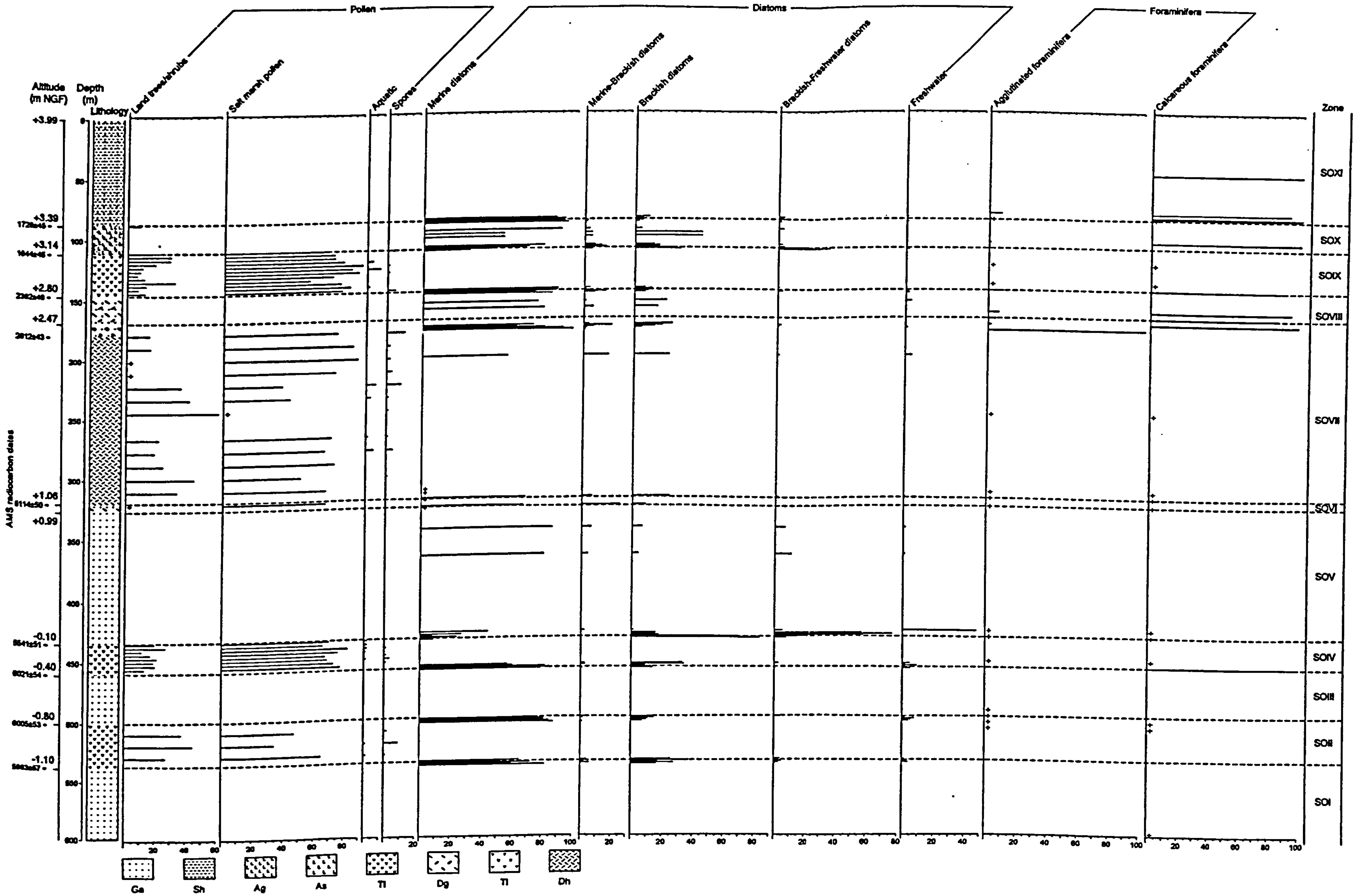


Fig. 6.6 Summary of palaeo-ecological data for the Estrébœuf. Data are presented as pollen, diatoms and foraminifera and have been subdivided according to their depositional environment.

Unit SOII: Lower peat (- 1.10 - - 0.80m NGF)

The lower samples of this deposit contained pollen suggestive of a salt marsh. Few diatoms were observed and no foraminiferal tests were recovered. By the middle of this peat layer, the pollen suggested that the site had become fully terrestrial, with tree species rising. A rise in sea-level must have occurred at this point, shown by a return to salt marsh conditions can be seen, with Chenopodiaceae pollen values rising once more. Also, nearing the stratigraphic contact, marine and brackish diatoms appeared, as did a few foraminiferal tests, suggesting low marsh or sand flats.

Unit SOIII: Sand (- 0.80 - - 0.40m NGF)

Once again we see pollen disappear from the record as would be expected. However, diatom and foraminifera counts from this unit were unexpectedly low with no satisfactory samples being obtained. The palaeoecological data from the contacts suggested tidal flat deposits, but with the very poor preservation it is not possible to be certain.

Unit SOIV: Peat (- 0.40 - - 0.10m NGF)

The diatoms and foraminifera were indicative of low marsh deposits at the upper and lower contacts. However, the pollen record becomes increasingly dominated by salt marsh pollen taxa towards the upper contact.

Unit SOV: Sand (- 0.10 – 0.99m NGF)

The fossil record was poorly preserved throughout this unit. No useful information was obtained until the upper contact when the tidal flat diatom species *A. delicatula* appeared, albeit in low quantities. The sudden appearance of *A. delicatula* may indicate a period of rapid deposition. Once again disappointingly foraminiferal tests were absent. Determining the origin of this sand deposit is therefore impossible.

Unit SOVI: Transition from sand to detrital peat (0.99 – 1.06m NGF)

The diatom and foraminifera preservation from this unit were poor and no firm conclusions can be drawn. It would appear that the site would have been inundated at high tide but was not fully marine. The pollen record showed open ground species with *Ulmus* and *Alnus* tree pollen present. The low amounts of Chenopodiaceae, less than 10%, indicates that this was not a salt marsh, placing sediment deposition at or around MHWST, indicating a relative fall in sea-level from unit SOV to SOVI.

Unit SOVII: Detrital peat (1.06 – 2.47m NGF)

No diatoms were sampled from this unit and the foraminiferal record recovered only a single sample containing *J.macrescens*. The pollen record was also quite poor but suggested an open ground habitat. It is likely that a salt marsh persisted at this time, indicating a change in relative sea-level had taken place since the deposition of unit SOVI.

Unit SOVIII: Sandy peat (2.47 – 2.80m NGF)

The diatoms indicate intertidal brackish water conditions at this time with *A. delicatula* present on occasions. The first complete foraminiferal record was obtained from this unit, revealing a low marsh or tidal flat environment. No pollen was obtained from this unit, suggesting that it is more likely to have been deposited under intertidal conditions, suggesting that the sea-level had risen once more.

Unit SOIX: Upper herbaceous peat (2.80 – 3.14m NGF)

The pollen record suggested that this unit undoubtedly represented a salt marsh environment, with Chenopodiaceae and Gramineae dominating throughout. The diatom record confirmed this with the presence of *Caloneis westii*, a species sometimes recorded on a low marsh. No foraminiferal tests were recovered, a common problem with salt marsh deposits. Although this unit represents a relative fall in sea-level since unit SOVIII, it is clear that it was still a tidally-dominated setting.

Unit SOX: Sandy silty clay (3.14 – 3.39m NGF)

Few pollen records were obtained but those that were suggested salt marsh taxa were still present. The diatom and foraminiferal species both point to brackish water conditions, most likely inter-tidal sand flats, which were tidally-dominated.

Unit SOXI: Sand with undifferentiated organic matter (3.39 – 3.99m NGF)

This final unit produced the most unexpected results, showing a wide range of foraminifera and very poor diatom and pollen preservation. It is possible that this unit has been re-worked and does not provide an *in-situ* deposit. The valley nearby the field site may have been subjected to major disturbance in recent years, with evidence of peat being extraction being undertaken further up the valley, leaving behind man-made ponds. It is possible therefore that the reworking is the result of anthropogenic influences. Drawing any conclusions about the sea-level signal of this unit therefore, might be misleading.

6.6 AMS radiocarbon dating

Twelve AMS radiocarbon dates were obtained from Estrébœuf in the Somme Valley, nine from the sample core SO BH9 and three from core SO BH8 (see Table 6.8).

It can be seen from Table 6.8 that the first three dates, when calibrated, are almost identical, making them inconclusive. The dates suggest that the theory proposed by the stratigraphic and palaeoecological data, a relative fall followed by a rise and a subsequent fall, is probably unfounded. This is discussed further later in the chapter.

A transgressive overlap was dated between unit SOIV and unit SOV in BH SO9, providing an age of 5541± 51 years BP (6436 - 6206 cal. years BP). The onset of the detrital peat, unit SOVII, which suggested a relative fall in sea-level was dated at 5114 ± 50 years BP (5985 - 5736 cal. years BP). The transgressive overlap was dated 2612 ± 43 years BP (2780 - 2622 cal. years BP), followed by a regressive overlap dated 2382 ± 49 years BP (2708 - 2332 cal. years BP). The last transgressive phase was dated 1844 ± 45 years BP (1880 - 1630 cal. years BP). The final date must be accepted with some caution. It was taken from the stratigraphic contact between unit SOX and SOXI, thought to be re-worked sediment. Although the date follows in sequence, whether or not it is indicative of a relative fall in sea-level is still unclear. The biostratigraphic data do not suggest a relative fall, however since the stratigraphy did indicate a change in the depositional environment.

In addition to the dates obtained from the sample core, three dates were obtained from BH SO8, further down-valley (see Fig. 3.4). The contact between the lower peat and sandy silt was dated, because it represented the deepest regressive overlap recorded at the Somme. This regressive overlap provided an age of 5015 ± 40 years BP (5652 - 5893 cal. years BP).

Stratigraphic position	Core	Lab code	Conventional Radiocarbon Age (years BP +/- 1 σ)	$\delta^{13}C_{PDB}$‰ +/- 0.1	Calibrated years (median)	Height (m NGF)
Regressive	SO BH9	AA-44083	5983 ± 57	-27.0	6966 – 6796 - 6669	-1.11
Transgressive	SO BH9	AA-44084	6005 ± 53	-27.2	6989 – 6827 - 6681	-0.73
Regressive	SO BH9	AA-44085	6021 ± 54	-27.9	7001 – 6821 - 6690	-0.33
Transgressive	SO BH9	AA-44086	5541 ± 51	-27.9	6436 – 6306 - 6206	-0.10
Regressive	SO BH9	AA-44087	5114 ± 50	-27.2	5985 – 5906 - 5736	+1.06
Transgressive	SO BH9	AA-44088	2612 ± 43	-27.4	2780 – 2748 - 2622	+2.42
Regressive	SO BH9	AA-44089	2382 ± 49	-28.3	2708 – 2654 - 2332	+2.80
Transgressive	SO BH9	AA-44090	1844 ± 45	-28.8	1880 – 1785 - 1630	+3.15
Regressive	SO BH9	AA-44091	1726 ± 45	-28.7	1730 – 1673 - 1529	+3.39
Regressive	SO BH8	CAMS-80704	5015 ± 40	-29.1	5652 – 5739 – 5893	+0.07
Transgressive	SO BH8	CAMS-80705	4255 ± 40	-27.0	4866 – 4833 - 4655	+0.37
Regressive	SO BH8	CAMS-80706	3490 ± 30	-28.9	3834 – 3757 - 3643	+1.51

Table 6.8 Summary of AMS radiocarbon data including conventional and calibrated ages

6.7 Sea-level change in the Somme Estuary, Northern France

Fig. 6.7 presents an age-depth plot of the sea-level index points obtained from the Somme Estuary. The horizontal error bar represents the AMS radiocarbon dating errors (1σ and 2σ). The reference water level for each index point is MHWST. The upward arrows represent marine transgressions and the downward arrows represent marine regressions. Those points with no arrow assigned represent AMS radiocarbon dates that were not assigned an indicative meaning due to a lack of palaeoecological data. The shaded boxes are those points for which palaeoecological data were insufficient to assign an indicative meaning and are therefore not valid sea-level index points.

The AMS radiocarbon ages obtained from the Somme cover a much longer period than those obtained from either the Pevensey Levels or the Canche Estuary, ranging from 6021 ± 54 years BP to 1726 years BP (7000 cal. years BP to 1700 cal. years BP). However, as previously indicated in Section 6.6, the first three dates are indistinguishable once calibrated (Stuiver & Reimer, 1993) and therefore require greater discussion before being accepted as sea-level index points.

The lowest stratigraphic boundary was dated at 5983 ± 57 yrs BP (6966–6796–6669 cal. BP). Stratigraphic evidence alone would suggest that a relative fall in sea-level had taken place, with the lower sand unit (SOI) being replaced by the lower peat (SOII). The pollen data suggested that this was a salt marsh deposit and the diatoms, although low in abundance, suggested that a relative fall in sea-level had taken place between the deposition of the sand and the deposition of the peat. No foraminiferal data were recorded. The second stratigraphic boundary shift presented a change from peat to sand, which would usually be indicative of a relative rise in sea-level. This overlap was dated 6005 ± 53 yrs BP (6989-6827-6681 cal. BP). No pollen or diatom data were recorded, but the foraminiferal results did suggest that the area could have been tidal flats (shown by the presence of the calcareous types *T. inflata* and *A. beccarii*). However, as can be seen in Fig. 6.7 the date appeared to be older than expected and once calibrated fell within the same age range as the date obtained for the overlap between the lower sand and lower peat. The third ambiguous date was obtained from the stratigraphic overlap from sand to peat, which would normally indicate a relative fall in sea-level. This overlap was dated at 6021 ± 54 yrs BP (7001-6821-6690 cal. BP). Salt marsh pollen and marine diatoms were recorded, but no foraminifera. Once again, the date appears to be older than expected and once calibrated falls within the same age range as the previous two dates.

On the basis of the pollen and diatom data, the lowest regressive overlap can be accepted as being indicative of a relative sea-level fall, as can the second regressive overlap, suggesting the date could possibly be correct. However, since all three dates obtained from the lower units are indistinguishable, it is impossible to accept the points as valid sea-level index points and must therefore be excluded from future sea-level reconstruction. These points are plotted on Fig. 6.7 with no indicative arrow, to allow them to be distinguished from the accepted sea-level index points. This means that prior to 6500 cal. years BP, the timing of relative sea-level change cannot be established from the existing data. Further research is required in particular the verification of the radiocarbon dates from the three contacts described above. The stratigraphy recorded from the period prior to 6500 cal. years BP clearly revealed that a number of sea-level fluctuations had taken place, although without confirmation of the age of the sediment, no timescale can be included in the sea-level interpretation.

The AMS radiocarbon date (date 14) obtained from the sample core SO9, at the stratigraphic overlap between the lower woody peat (unit SOIV) and the sand layer (unit SOV), provided an age of 5541 ± 51 years BP (6306 cal. years BP). The sedimentary record suggested that a potential rise in relative sea-level could be detected. However, the lack of palaeoecological data means it has not been assigned an indicative meaning.

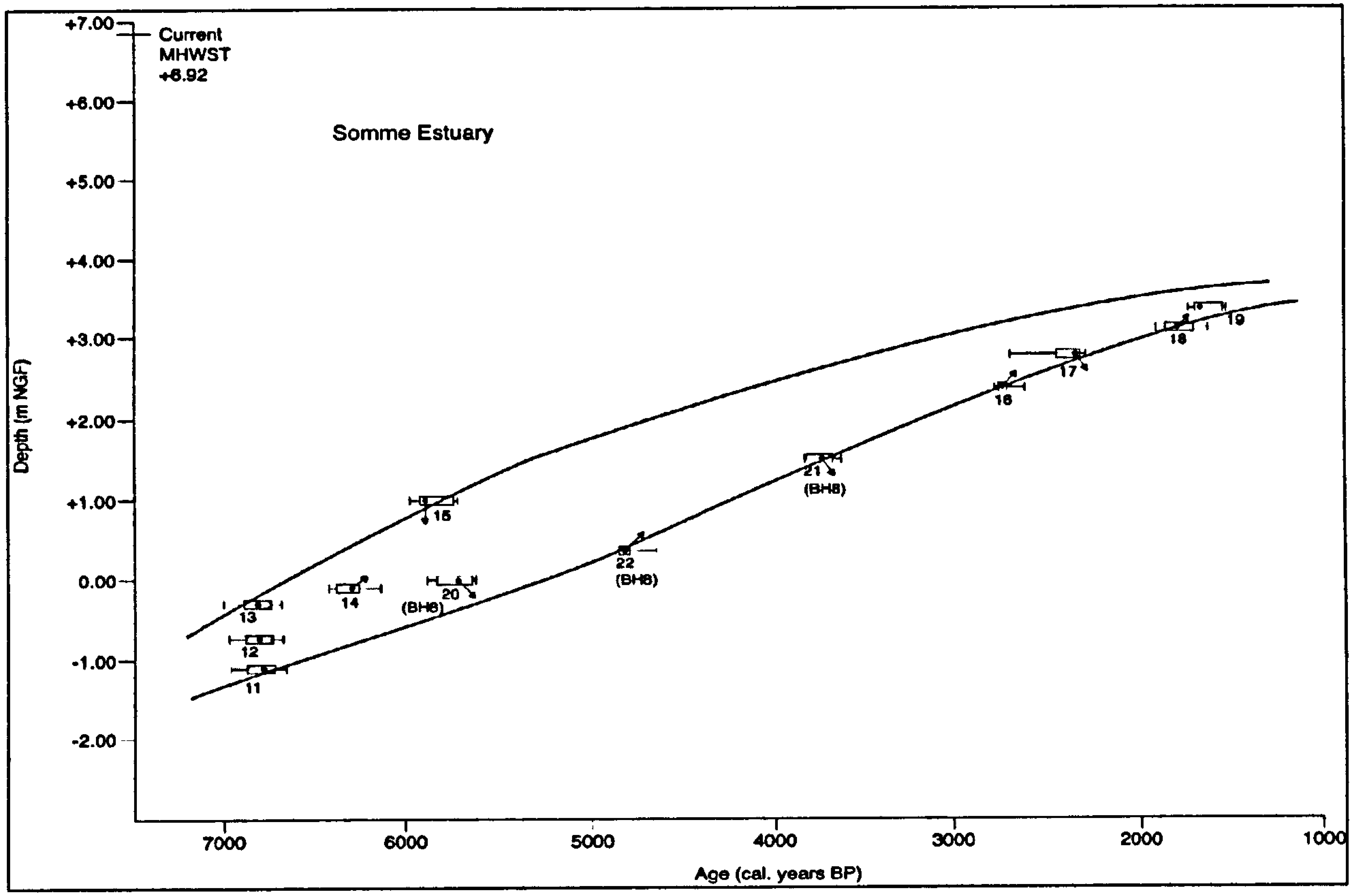


Fig. 6.7 Age-depth plot of sea-level index points from the Somme Estuary, Northern France

The horizontal error bar represents the AMS radiocarbon dating errors (1σ and 2σ). The arrows indicate whether a marine transgression or regression took place. If no arrow is assigned, no indicative meaning could be determined. Shaded boxes refer to points which are not valid sea-level index points.

The first valid sea-level index point marks a regressive event (date 15) considerably later at around 5114 ± 50 years BP (5906 cal years BP). This fall in sea-level was marked by the regressive overlap recorded between unit SOVI, a transitional unit and unit SOVII, a detrital peat. The palaeoecological data from the transition unit indicated that the area was still subject to flooding at high tide, but did not suggest it was a salt marsh deposit. The absence of sand throughout the detrital peat (unit SOVII) provided the first evidence for a reduced marine influence and the pollen record supported this. Gramineae pollen dominated the record, with varying amounts of tree pollen present (up to 80% in one sample), suggesting the unit was deposited under a relatively low sea-level between 5114 ± 50 years BP (5985 - 5736 cal years BP) and 2612 ± 43 years BP (2780 - 2622 cal years BP).

A regressive overlap was also recorded in BH SO8 (date 20), closer to the present day position of the River Somme (see Fig. 3.4), and was assigned an age of 5015 ± 40 years BP (5652 - 5893 cal years BP). Although the timing agrees quite closely with that in BH SO9, it can be seen on the age-depth plot (Fig. 6.7) that the altitude of this regressive event is considerably lower in BH SO8 than in the sample core BH SO9. It is possible that this is the result of sediment compaction (refer to section 6.7). BH SO8 had almost 3m of medium-grained sand overlying the detrital peat, which will almost certainly have caused the peat to compact, whereas BH SO9, had only 1m of sand lying on top of the 1.41m of detrital peat. If all the index points obtained from BH SO8 were raised by about 1m and were corrected to MHWST, the points would plot in line with those from BH SO9, showing a smooth, gradually rising sea-level.

The dates from BH SO8 provided valuable information about the sea-level changes that took place *c.* 6000 cal. years BP and 2800 cal. years BP, a period which was not covered by the sample core BH SO9, demonstrating the value of obtaining sea-level index points from a variety of positions across the estuary. If dates had only been collected from the sample core, no data would have been provided for a 3000 years period. By obtaining age data for a number of stratigraphic positions across an estuary a more complete picture can be acquired.

The next transgressive overlap took place 2612 ± 43 years BP (2780-2622 cal. years BP), shown stratigraphically by the change from detrital peat (unit SOVII) to sandy peat (unit SOVIII). The diatom and foraminiferal record from the sandy peat indicated that tidal flats were present at this time, confirming that a rise in relative sea-level had taken place since the deposition of unit SOVII. The transfer function places this deposit at MHWST –1.20m, suggesting the site was inter-tidal at this time reinforcing the theory that it may have been tidal flats. However, this was to be a relatively short-lived high sea-level, and by 2382 ± 49 years BP (2708 – 2332 cal. years BP) sea-level had fallen once again.

The regressive overlap seen in BH SO9 at 2382 ± 49 years BP (2708-2332 cal. years BP) marked a change from sandy peat to the upper herbaceous peat (unit SOIX). The pollen record revealed this deposit to be a salt marsh. A clear transition could be seen throughout the peat, starting with salt marsh taxa being recorded near the lower stratigraphic boundary. A dry period then followed, with poor pollen preservation and the presence of some tree pollen. Toward the top of the peat unit, salt marsh taxa returned, signalling the sediment was once again being deposited under a tidally dominated environment.

The end of the upper herbaceous peat marks the final transgressive episode recorded at the Somme. The change to sandy silty clay was dated 1844 ± 45 years BP (1880 - 1630 cal. years BP). In the lower samples salt marsh pollen remained, showing that the area was still inter-tidal, most likely low marsh deposits. However, the diatom and foraminiferal record undoubtedly showed a return to a tidal flat setting.

The final date obtained from the Somme must be accepted with some caution. The sediment revealed a return to more organic deposition, initially suggesting a fall in relative sea-level had taken place, possibly allowing salt marsh vegetation to colonize the area once more. The pollen and diatom preservation was poor, not uncommon in oxidised sediments, since the presence of iron oxide is known to damage the diatom frustules (Mayer *et al.* 1991). A wide range of foraminiferal species was recorded, indicating a number of depositional environments, which meant no palaeo-tidal or depositional environment could be determined. It was therefore not possible to assign an indicative meaning to this date.

A rising mid-to late-Holocene sea-level can be observed in the Somme Estuary. The stratigraphic record reveals a number of potential transgressive and regressive events. However, AMS radiocarbon dating and palaeoecological analyses failed to conclusively determine the age and origin of all of these sediments. Further analysis is required on those stratigraphic contacts where an index point could not be assigned, in particular verification of the radiocarbon dates. Unfortunately, this was beyond the scope of this research.

6.8 Estimate of the compaction of sediments

It can be seen in Fig. 6.8 that the sea-level index points obtained from BH SO8 plot below those obtained from BH SO9, suggesting that the sediment has been subject to compaction. The transgressive overlap recorded in BH SO8 (date 22) was dated to 4255 ± 40 years BP (4866 - 4655 cal. years BP), but its altitude is well below the regressive overlap dated 5015 ± 40 years BP (5652 – 5893 cal. years BP). The regressive overlap recorded in BH SO8 and dated 3490 ± 30 years BP (3834 - 3643 cal. years BP) also appears to have been compacted. If these three sea-level index points are corrected for compaction, this regressive overlap at 3834-3643 cal. years BP could plot slightly above present day MTL, suggesting why previous work in the Somme had concluded sea-level rose above present day sea-level (Agache *et al.*1963).

If Allen's (1999) equation is applied to the cores from which sea-level index points have been obtained, the following results can be seen (Table 6.9). Detailed calculations can be found in Appendix IV. The three unreliable sea-level index points have been excluded from the discussion.

The data show quite clearly that differential sediment compaction has taken place between the sample core and SO BH8. Sediments appear to have compacted by up to 40% in the case of the mid-core transgressive overlaps. However, again the fact that sand dominated the upper sediments in the French boreholes has meant that it has not been possible to apply an accurate correction for compaction to those sea-level index points taken from peat-sand overlaps. Once plotted against the original observed age-depth data from the estuary.

It must be noted here that those sea-level index points that have remained unchanged, do not indicate that no compaction has taken place. These stratigraphic boundaries were dominated by sand sediments, for which it is assumed relatively little compaction has taken place (Allen *pers comm.).* Thus, no estimate of decompaction has been provided for the sand units.

Sea-level index point	Original depth (m NGF)	Estimated decompacted depth (m NGF)	Estimate of compaction (m)	Percentage compaction (%)
Sample Core SLIP4 Transgressive overlap	-0.10	+0.61	0.71	17
Sample Core SLIP5 Regressive overlap	+1.06	+1.06	0	0
Sample Core SLIP6 Transgressive overlap	+2.42	+3.73	1.31	40
Sample Core SLIP7 Regressive overlap	+2.80	+2.80	0	0
Sample Core SLIP8 Transgressive overlap	+3.15	+3.33	0.18	10
Sample Core SLIP9 Regressive overlap	+3.39	+3.42	0.03	3
SO BH8 Lower sand to peat contact	+0.07	+0.07	0	0
SO BH8 Lower peat to sand contact	+0.37	+0.52	0.15	4
SO BH8 Upper sand to peat contact	+1.51	+0.71	0.20	6

Table 6.9 Estimates of sediment compaction on sea-level index points from Estrébœuf

Fig. 6.9 shows that once the sediments have been corrected for compaction, a smoother sea-level curve is produced. However, it can be seen that two anomalous points still remain, both taken from the sample core at sand-peat overlaps. These come from points that could not be corrected for compaction using the current data set and model, because they were both taken from the top of sediment units from which a compaction estimate was not possible since it was an intercalated unit. This again displays the limitations imposed in performing such a correction using exploratory data.

The estimate of compaction presented above does however assist in the comparison between the sample core and BH SO8. Excluding the two erroneous dates described above, the overall pattern of sea-level change at the Somme presents a smoothly rising relative sea-level curve, eliminating the major fluctuations often exhibited on sites from northern France. Once again an S-shaped curve can be seen, a matter which will be discussed again in Chapter Eight.

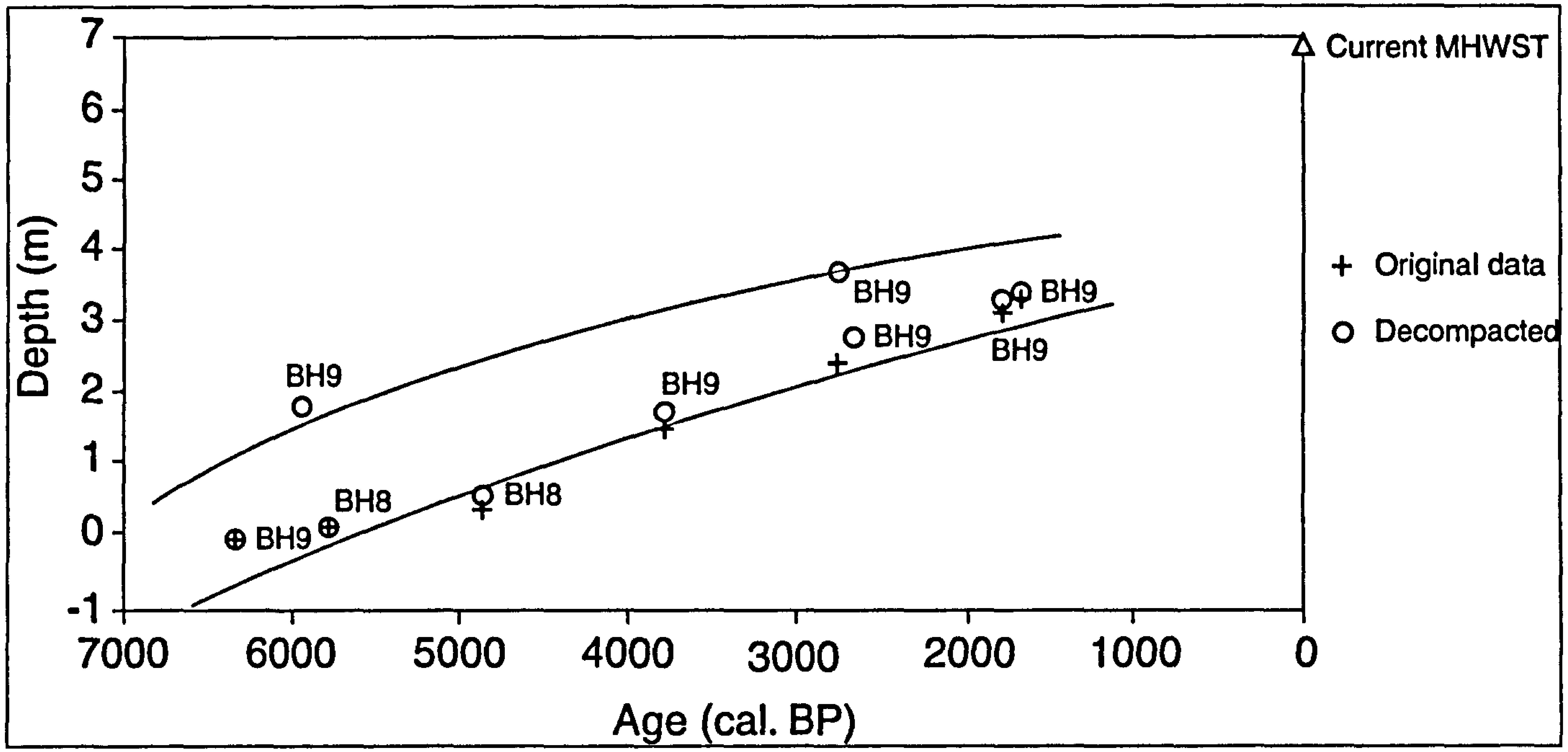


Fig. 6.8 Age-depth plot of original and estimated decompacted data for the sea-level index points from Estrébœuf

The estimates of compaction from Estréboeuf once again cast doubt over whether the fluctuation observed along much of the northern coastline of France are actually the result of a fluctuating sea-level or whether they are simply a result of the methodology and analytical tools employed in the research. It would appear that by correcting for compaction the altitudes of the sea-level index points at Estréboeuf become more comparable between the sample core and SO BH8, eliminating any major fluctuations observed in the pattern of sea-level rise. Once again several limitations are placed on the estimates, most significantly empirical data on the compressibility of sand, which is considered incompressible here, is required and if possible altitudes of basal peats should be determined to provide a reference point which has not been affected by compaction.

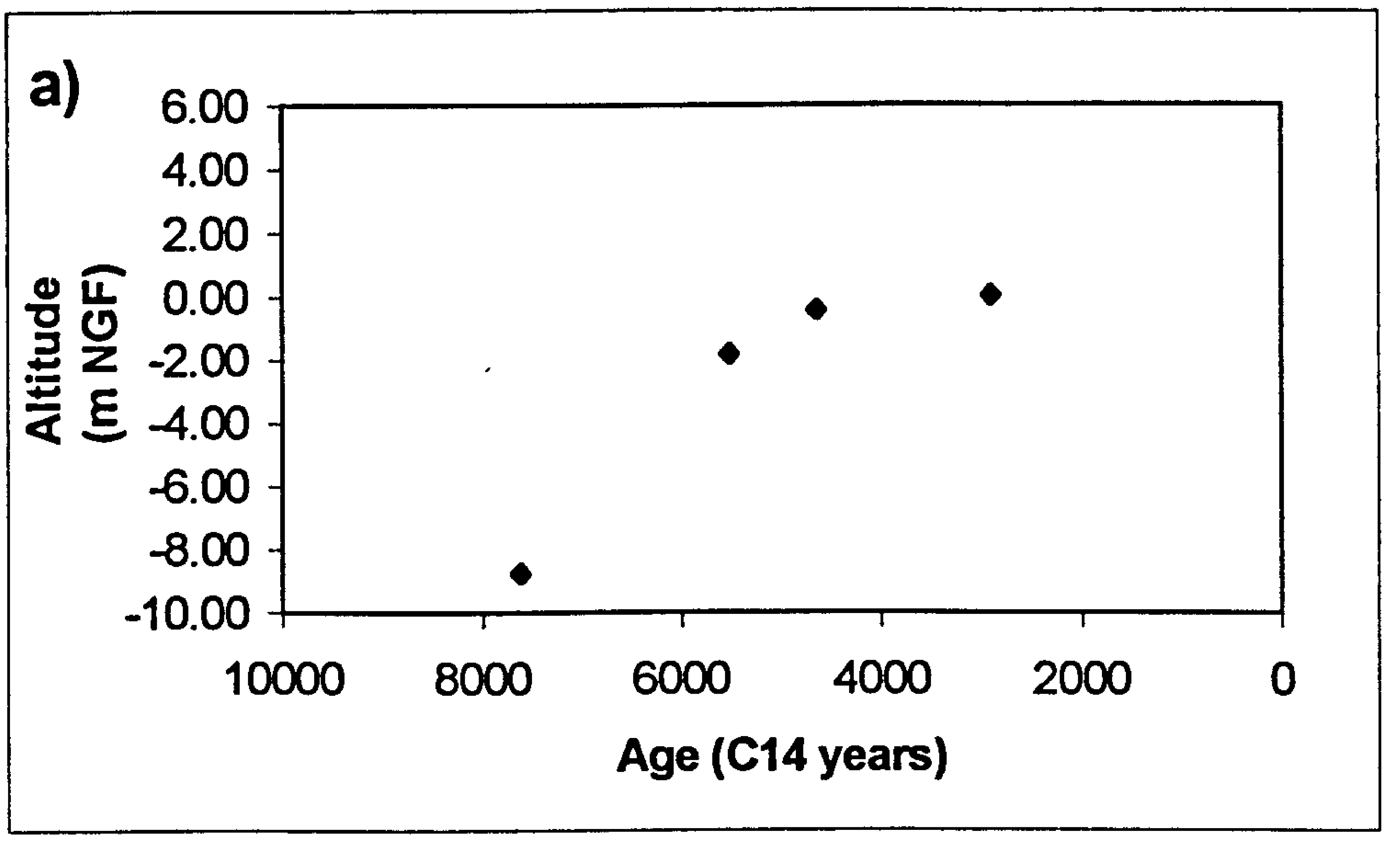
6.9 Comparison with previous findings in northern France

Previous research along the coast of northern France has resulted in a number of views relating to the pattern of Holocene sea-level change. As discussed in Chapter Two, one of the greatest debates surrounding Holocene sea-level change in northern France focuses on whether or not past sea-level rose above present day mean sea-level (Agache, 1963; Ters, 1986; Lambeck, 1997). Results from the Canche Estuary do not appear to show any evidence to support the theory that sea-level in this particular estuary has risen above the present day sea-level.

The age-depth plot based on all previous work along the Picardie coast shows that the mid- to late Holocene period were described as a fluctuating, rising sea-level, as discussed in Chapter Two (Agache *et al.*1963; Ters, 1986). However, the age-depth plot presented for the Canche does not show these dramatic fluctuations. Fluctuations such as those described for this region can again be criticised, as previously stated "...a 5m oscillation suggested by Ters (1973, 1986), requires a cyclic change in ice volume equal to about 30% of the Scandinavian ice sheet within about 1000 years or less" (Lambeck, 1997 p.2).

It would appear that the methodology employed in a study controls the outcome. Thus comparing studies that have used different techniques can produce quite different results (refer to Chapter Nine). In an attempt to correct for this, Fig. 6.12 has been produced. Depths are plotted relative to NGF, since for much of the data a reference water level such as MHWST was not used. The data plotted on this graph has been taken from previously published data. However, instead of simply plotting the published curves, only those points taken from peat contacts at single coring sites have been plotted. This allows MHWST to be assumed and eliminates the problems of compaction and consolidation of the sediments. In order to do this, some of the previous studies had to be disregarded because data was not based on accurate radiocarbon dating and no information was provided about the indicative meaning. The study by Agache *et al.* (1963) has not been used because no reliable sea-level index points were obtained, samples were not radiocarbon dated and very little altitudinal data was provided. The study by Morzadec-Kerfourn (1969) has also been excluded because data were obtained from the Brittany coastline, which has different local controls and will therefore potentially produce a quite different sea-level curve to that from Picardie and Pas-de-Calais. Ters' (1986) research has not been included because the sea-level curve was based on data taken from a number of sites, and this technique has been proved to be erroneous.

Once the above studies had been excluded, the only comparable studies that were included were Ters *et al.* (1980); Delibrias & Guilcher (1971) and Mariette (1971). In Fig. 6.9 a/b the data that was collected by Ters *et al.* (1980) based on pollen, foraminfiera and radiocarbon has been re-plotted. Two cores were obtained from the lower Somme Estuary. The data in Fig. 6.9 a/b have been obtained from Ters *et al.*1980 p. 16. In Fig. 6.9a only dates obtained from the core Rue 3 have been plotted. In Fig. 6.9b dates from core Rue 3 and core M21 have been plotted on the same graph. It can be clearly seen from the two graphs in Fig. 6.9 that a quite different pattern of sea-level change can be identified when the data from more than one coring position is plotted as a single age-depth plot. Fig. 6.9a produces a fairly smooth rising relative sea-level, whereas Fig. 6.9b appears to show a more variable rising rate of sea-level with oscillations superimposed on the trend. This once again highlights the problems caused by differential compaction and tidal range.



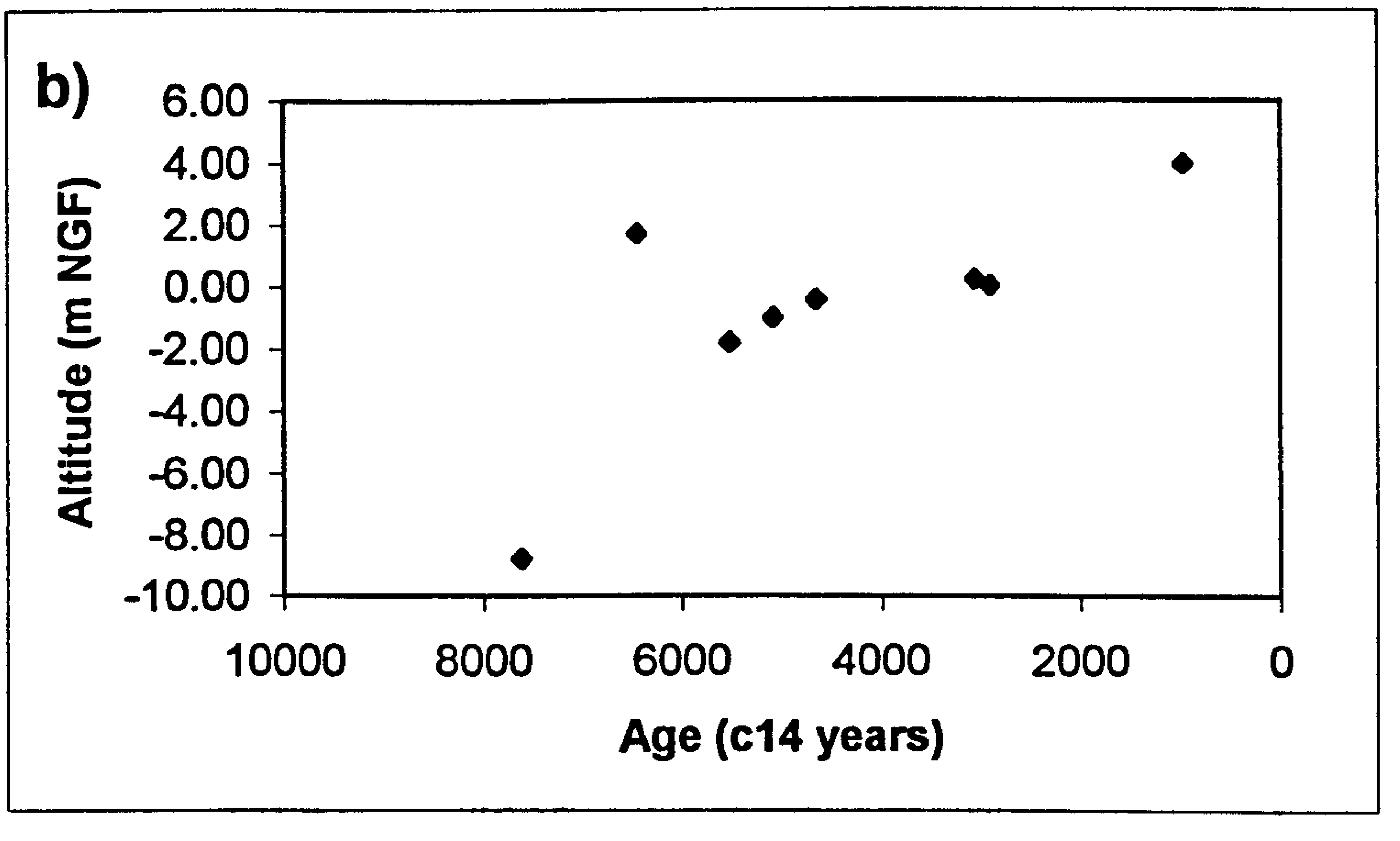
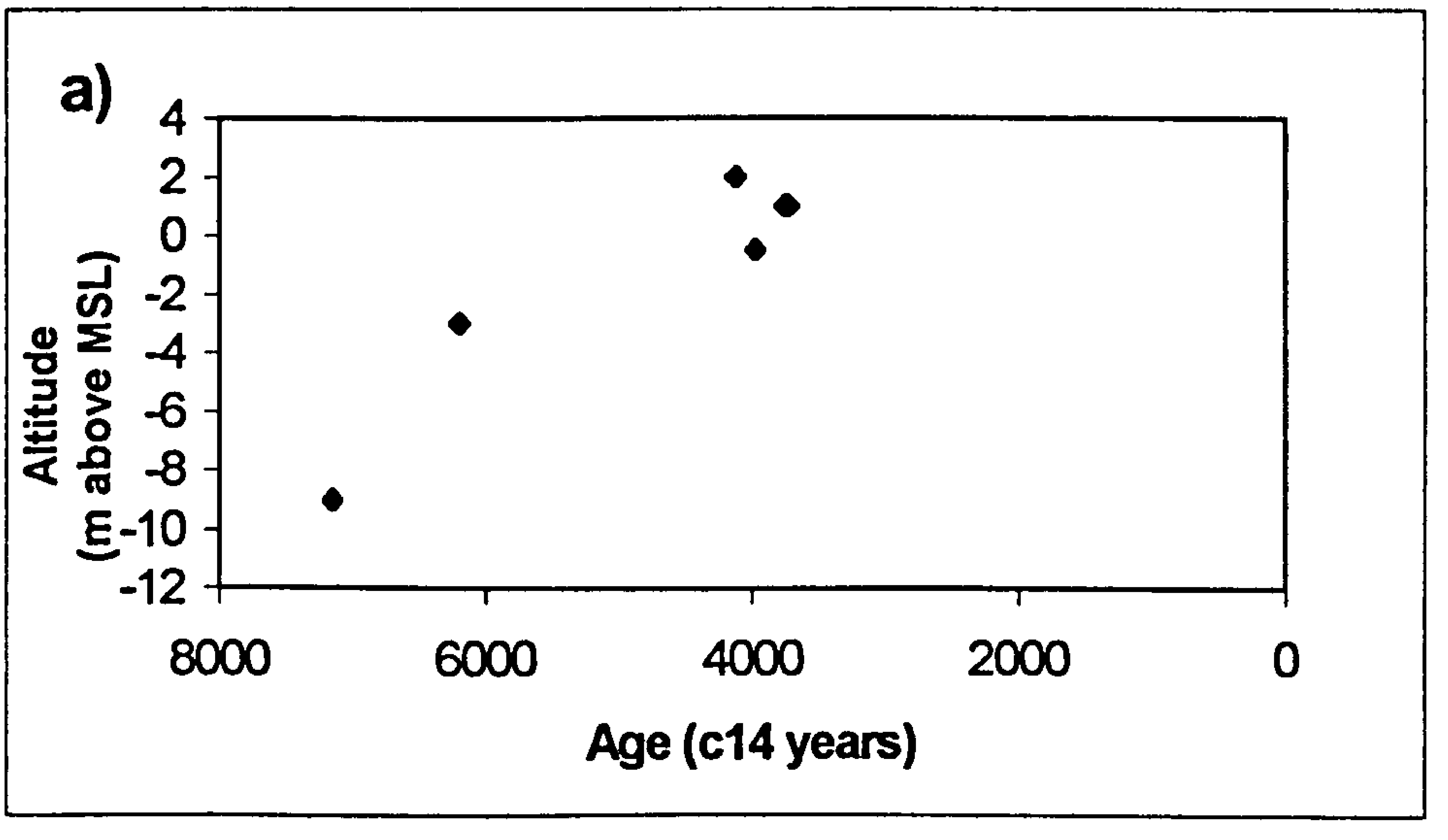


Fig. 6.9 Data taken from Ters *et al.* (1980) a) Data taken from a single core Rue 3 and b) Data taken from two cores Rue 3 and M21.

The data collected by Delibrias & Guilcher (1971) from the Atlantic and Channel coasts were treated in a similar manner, producing Fig. 6.10a/b. Radiocarbon dates were obtained from Table 1 (Delibrias & Guilcher 1971 p. 135) and were selected on the basis of geographical location and age range. Fig. 6.10a contains data from N. Latitude 50° 24' and Longitude 1° 36' and Fig. 6.10b contains data from a range of locations in northern France. It can be seen that once again the use of multiple sites to produce a single sea-level curve lead to a number of methodological introduced errors.



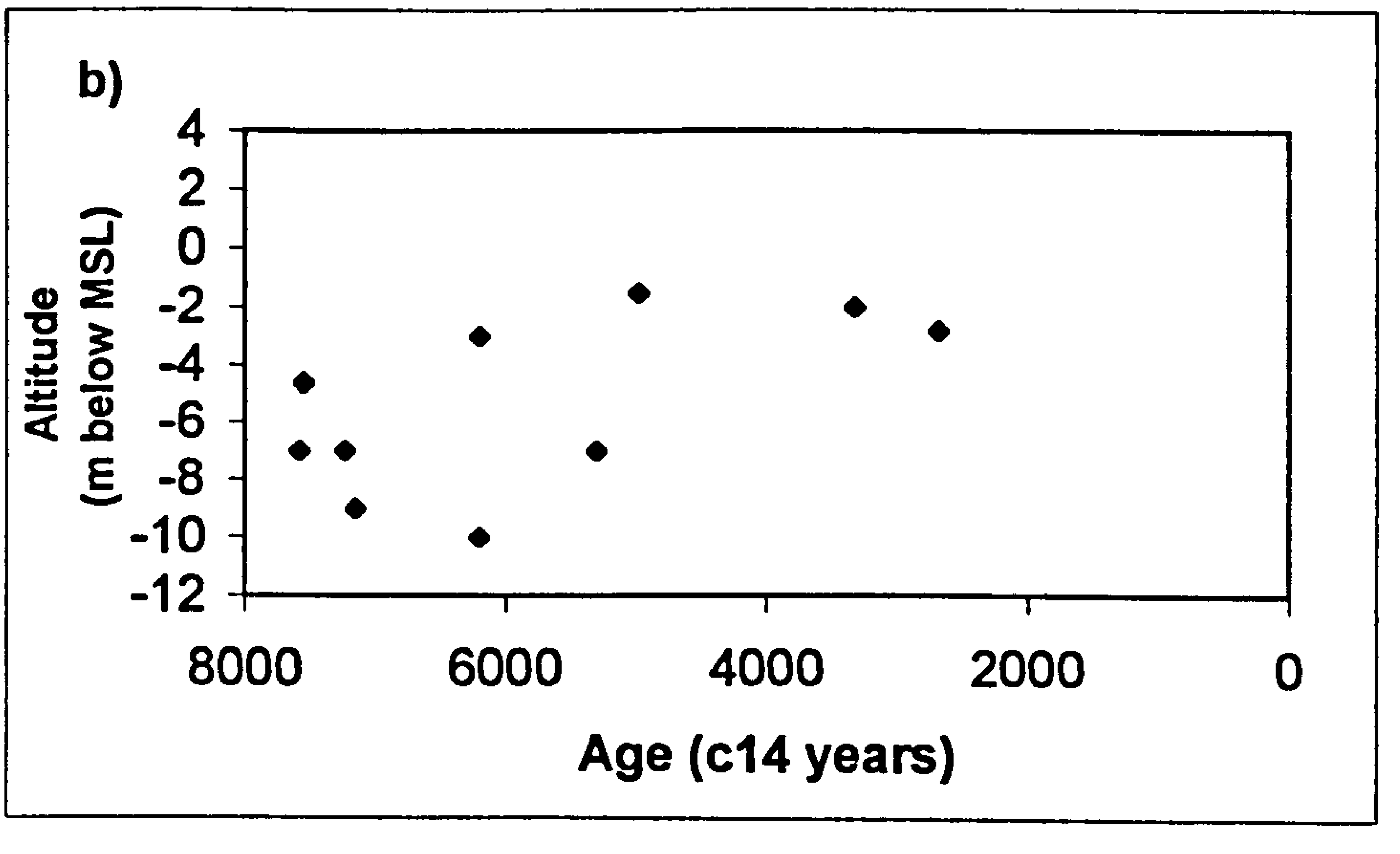


Fig. 6.10 Re-plotted sea-level data after Delibrias & Guilcher (1971)

a) Data taken from a single site b) Data taken from multiple sites

The data taken from Mariette (1971) was also treated in a similar manner, and produced a similar result (see Fig. 6.11a/b). Fig 6.12a contains only radiocarbon data obtained from Camiers, whereas Fig. 6.11b contains all the data that Mariette (1971) used to produce the relative sea-level curve (Mariette 1971 Fig.6 p.145).

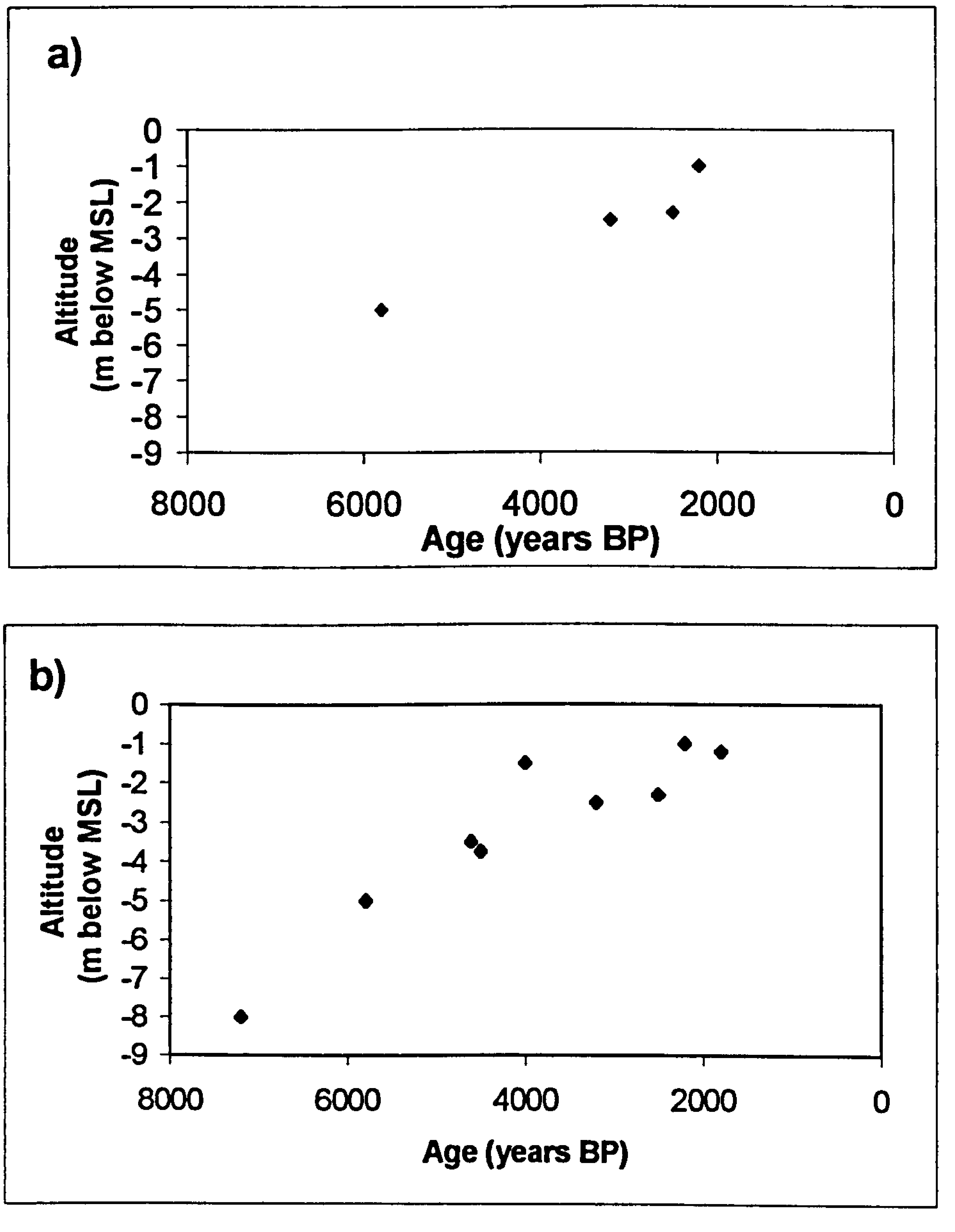


Fig. 6.11 Re-plotted sea-level data from Mariette (1971)

a) Data taken from a single site Camiers. b) Data taken from multiple sites

If the data that has been re-plotted from the single sites is then plotted on a graph to allow a comparison, rather than with the aim of producing a single curve, then several major differences can be observed (see Fig. 6.12).

The first important feature to note about all the data points is that none of them plot above current MSL or MHWST, which are 5.35m and 4.87m respectively. All the data points are comparable and can be assumed to represent deposition at approximately MHWST. The highest sea-level index point obtained actually comes from the Canche site (CA BH10), at +4.20m NGF and dated 2230 ± 40 years BP.

The second feature to notice is that none of the data series exhibit any major oscillations, such as those described by Ters (1973). Thirdly, the data points taken from Mariette's (1971) study plot well below all the other dated points, indicating that there has probably been significant sediment compaction at Camiers, once again highlighting the need to correct for such factors. This could indicate that the area in this northern part of France is experiencing considerable down warping or crustal subsidence. It can also be seen that the curves from the Picardie coast (Agache *et al.* 1963) and that obtained from the Canche Estuary (this research) plot above those from the Atlantic coast (Ters, 1986). The curve produced for Calais (Mariette, 1971) does not plot above other sites. This could be the result of the method employed in that study. However, it is more likely that either the location of the samples was significantly lower in altitude due to their position in the estuary or that differential compaction of the sediments has taken place, lowering the altitude of the peat surface at some of the sites.

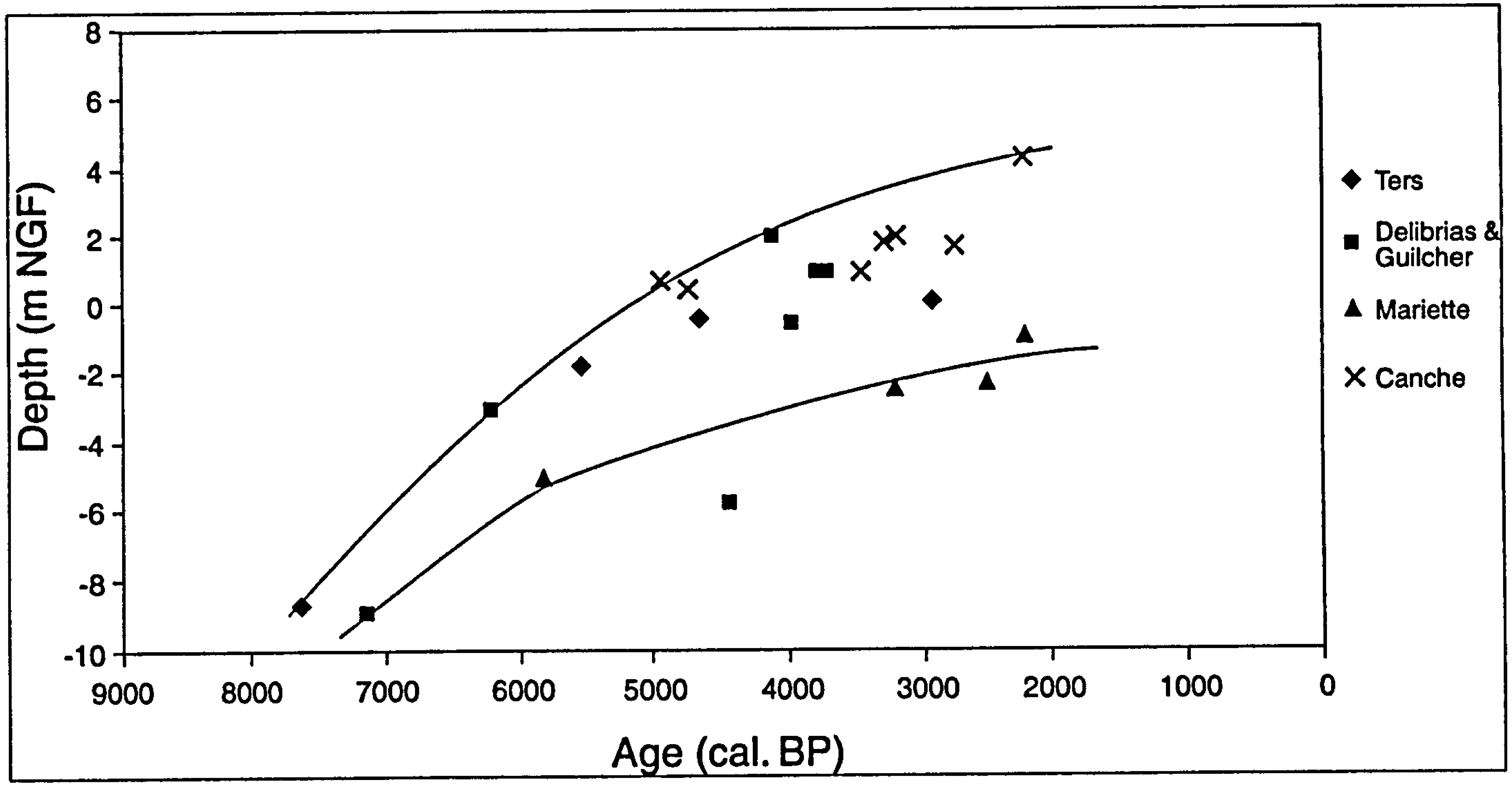


Fig. 6.12 Comparison between age-depth points taken from northern France

After: Ters *et al.* (1980), Delibrias & Guilcher (1971), Mariette (1971) and points from the Canche Estuary

Carrying out a comparison between sites based solely upon altitudinal data provides mis-leading results. Much of the previous work has not been corrected for compaction and therefore if a comparison is to be made it must be based on uncorrected data. Therefore, any comparative discussions are based on uncorrected altitudes.

The above comparison clearly shows the importance of using similar methodologies when performing comparative studies, and emphasizes the need for a standard technique to be employed when reconstructing palaeo-sea-level at sites that exhibit similar coastal features. The need to correct sediments for the effects of compaction also becomes more important when attempting comparative studies.

A comparison between the timings of the transgressive events (see Table 6.10) allows a more reliable and thorough comparison, identifying several similarities to be observed between the sites in northern France at a more regional scale.

All the accepted sea-level index points obtained from Estrébœuf ranged between *c.* 6000 cal. years BP and 1800 cal. years BP, providing an ideal time frame within which to draw comparisons with previous research undertaken in northern France. In a similar manner to the comparison carried out in Chapter Five, the sea-level curves produced from the Atlantic coast (Ters, 1986), Brittany coast (Morzadec-Kerfourn, 1975) and Picardie coast (Mariette, 1971) plus the sea-level index points obtained from the Somme, have been plotted together on a single graph. Once again this is not an attempt to produce a single age-depth plot for the region, but is a means of comparing different sites. However, as with the Canche this type of evaluation highlighted the methodological errors involved in carrying out comparisons using data that were not collected using the same techniques. A number of studies were excluded on the basis of their methodologies The same re-evaluated data has been used here to plot the findings of previous research against the findings from the Somme (Fig. 6.14).

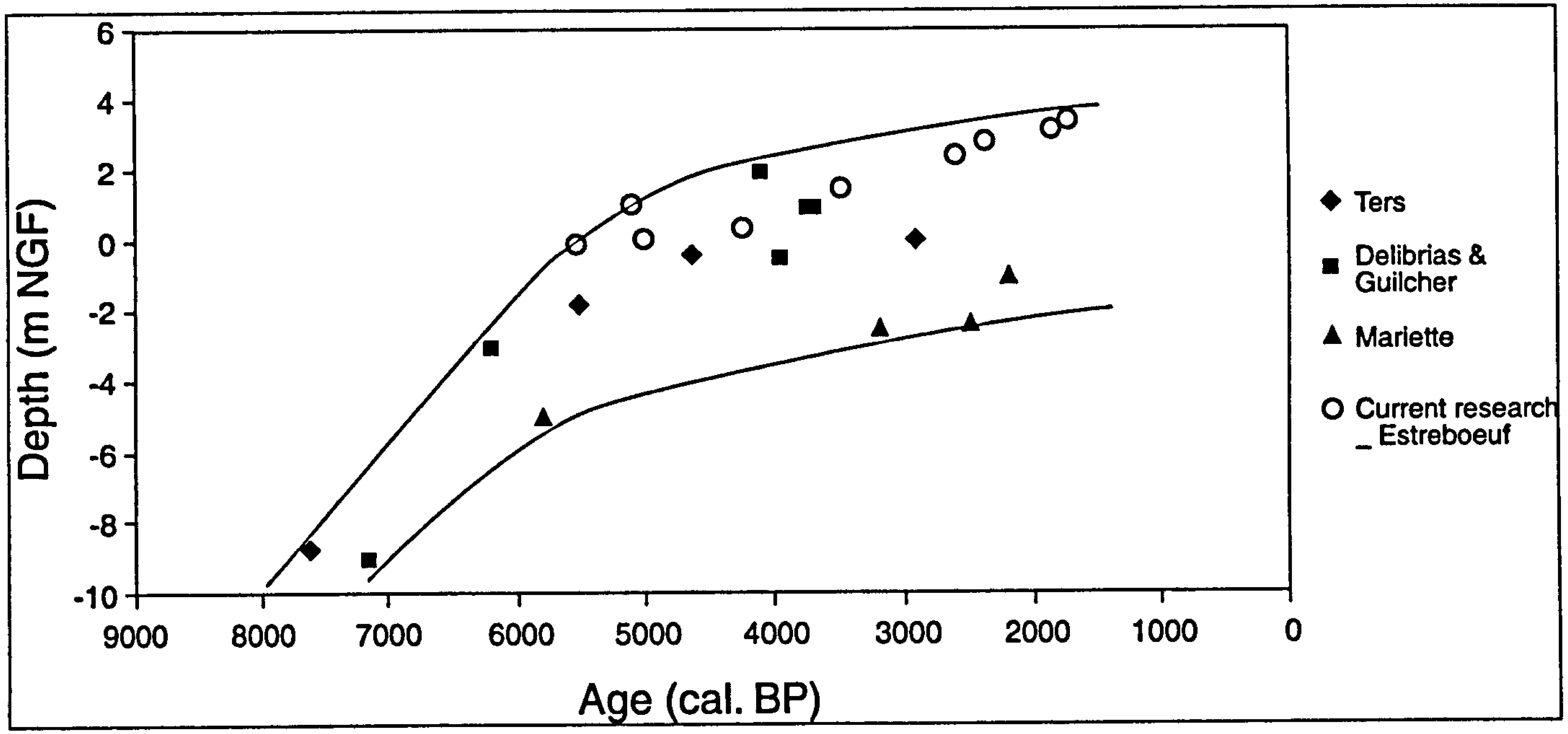


Fig. 6.13 Comparison between age-depth points taken from northern France

After: Ters *et al.* (1980), Delibrias & Guilcher (1971), Mariette (1971) and points from this study in Estrébœuf, Somme Estuary

The comparison highlights a number of key features. Firstly, no points plot above current MSL or MHWST, 5.49m and 5.77m at Cayeux, which had previously been thought (Agache *et al.* 1963), which could possibly be the result of the inherent errors caused by employing different methodologies. Secondly, the data taken from Ters *et al.* (1980) shows no major oscillations. This highlights the need to examine data from single estuaries and not combine data points into a single sea-level curve. Thirdly, Mariette's (1971) data plot well below the other sites, indicating that differential compaction and consolidation of the sediments may have taken place. Finally, the data from Estrébœuf plots above the data from previously published work.

The timings of the mid- to late- Holocene transgressive episodes show close similarities when examined at the regional scale (refer to Table 6.10). The dabate about whether regional transgressions/regressions should be identified is discussed in Chapter Seven. The earliest transgression recorded at Estréboeuf took place *c.* 5,300 cal. years BP. A similar event was recorded along the Atlantic coast, although slightly later. Also of interest to note is the event seen to occur at the Canche and Somme estuaries, dated to 2,800 cal. years BP and 2,700 cal. years BP respectively. The discussion below focuses more on the significance of this event; however it was clearly a regional scale transgressive episode. The last marine transgression, seen to occur in the Somme around 1800 cal. years BP, corresponds well with the marine transgression recorded along the Atlantic coast (Ters, 1986), once again indicating the possibility of regional scale sea-level changes.

Of particular interest are the late-Holocene transgressive events recorded 1300 and 1100 years BP at the Atlantic and Picardie coasts. These events were not detected at the Somme, possibly signalling that local controls were influencing the pattern of sea-level change, or that the signal was lost in the upper minerogenic sediments.

The first transgressive event recorded at the Canche *c.* 3,500 years BP was also recorded on the Brittany coast (Morzadec-Kerfourn, 1975), although the magnitudes of change were quite different (see Fig. 6.13). Along the Picardie coast a transgressive event was seen to have taken place slightly later at *c.* 3,000 years BP (Mariette, 1971). The second transgressive overlap recorded at the Canche provided a date of *c.* 3,200 years BP. This indicates that the same rise in relative sea-level took place slightly earlier at the Canche than in the Basse-

Somme at slightly different altitudes. The event recorded at *c.* 2,800 years BP was not recorded elsewhere along the northern coast of France.

The third transgressive event to occur at the Canche was recorded at *c.* 2,200 years BP. Similar transgressive events were also recorded along the Atlantic coast (Ters, 1986) and along the Picardie coast (Mariette, 1971) (seeFig. 6.14).

Previous work has also documented a series of transgressive episodes since 2,000 years BP. There did not appear to be any evidence to suggest that such phases had taken place at the Canche. The event recorded *c.*1900 years BP (Mariette, 1971) was not recorded at the Canche, however a similar apparently regional event was recorded by Ters (1973). Changes in the sediment were visible throughout the upper inorganic units at the Canche, which suggested possible changes in sea-level. However, since it was not possible to date these inorganic units using AMS radiocarbon dating, further research could consider using alternative dating techniques and greater examination of the particle size distribution throughout the upper sandy silty units to monitor the changes.

The transgressive event that took place *c.* 3,500 years BP was recorded at both the Canche and the Somme by this study and previous research (Mariette, 1971), suggesting that a regional sea-level signal has been detected. However, this event was not recorded along the Atlantic coastline, although a transgressive event of lesser magnitude can be seen to take place considerably later *c.* 3000 years BP (Ters, 1986). A high sea-level was recorded in the stratigraphy recorded at the Canche in BH CA10 (+4.3m NGF) c. 2230 ± 40 years BP, but no evidence existed to suggest sea-level rose above 5.35m NGF (present mean sea-level). Many authors have argued that insufficient evidence exists to support these high sea-level events (Ters, 1986, Lambeck, 1997). This high sea-level could therefore be an event only recorded along the Picardie coast, possibly highlighting the importance that local factors, such as subsidence of the land, play. Further evidence of the sediments and supplementary work along the Picardie coastline would be needed for any conclusive evidence to be provided.

Age range	Channel coast Calais & Dunkerque (Ters, 1986)	Brittany (Morzadec-Kerfourn, 1975)	Picardie (Mariette, 1971)	Villiers (Canche Estuary)	Estrébœuf (Somme Estuary)
0 – 1000	1100				
1000 - 1500			1900		
1500 – 2000	1800		2300 2200		1800
2000 - 2500	2200			2200	
2500 – 3000	3200		3200	2800	2700
3000 - 3500		3500		3500 3200	
3500 – 4000	4000		4300		
4000 - 4500		4500	4500		
4500 – 5000	5000				
5000 - 5500					5300
5500 - 6000	6100	6000	5800		
6000 - 7000		7000			6800
7000 - 9000	7400				

Table 6.10 Comparison of transgressions in N. France, dates are given in ^{14}C years BP

Unlike at the Canche and the Pevensey Levels, previous sea-level reconstructions have been attempted at the Somme Estuary (Agache *et al.* 1963, Ters *et al.* 1980, Buen et Broquet, 1983 and Ters, 1986). As discussed in Chapter Two, Agache *et al.* (1963) used stratigraphic and archaeological data to reconstruct Holocene sea-level but did not obtain any radiocarbon dates and therefore, their results are not included in this comparison.

Ters *et al.* (1980) proposed a comprehensive pattern of Holocene sea-level change for the French Atlantic and Channel coasts. The study detailed eight episodes of marine sedimentation. Once again a regressive event was recorded at 7300 years BP. This was followed by a rise in relative sea-level, seen until 5200 years BP, when peat formation began, compared with around 5800 years BP at the Somme (Ters *et al.* 1980). At this time, the pattern of sea-level change proposed by Ters *et al.* (1980) differs considerably to that recorded at Estrébœuf. Ters *et al.* (1980) describe a regressive event between 4800 and 4500 years BP, followed by a transgressive event at 3350 years BP, rising to –3m below NGF. Between 2900 and 2600, a fourth regressive event was recorded, followed by a rise *c.* 2200 years BP, which reached present day level but did not exceed it. The research by Ters *et al.* (1980) found evidence suggesting that at around 2000 years BP, sea-level was above present day mean.

To complicate matters further, evidence for the existence of a shingle barrier across the mouth of the Somme has also been presented (Buen & Broquet, 1983), which may cause the sea-level signals to be affected, as has been seen at the Pevensey Levels and Romney Marsh in south east England. As discussed in Chapter Two, a five-stage model of barrier evolution was proposed. The pattern observed at Estrébœuf seems to be consistent with the pattern described by Buen & Broquet (1983). The first stage, between 8000 and 5000 years BP, describes how the sea advanced and estuarine silts were deposited. This was followed by a sharp marine transgression at around 5000 years BP (Mariette, 1971), which caused erosion of these silts and lead to the deposition of the blue-grey clay. Buen & Broquet (1983) describe the extension of the coastal barrier from 3000 years BP. This barrier extension could provide an explanation for the lack of sea-level index points obtained from the sample core BH SO8 between 6000 and 3000 years BP, a period during which time an extensive salt marsh was able to develop (the detrital peat). It is therefore possible that the peat recorded at Estrébœuf in BH SO9, dated *c.* 5900 cal. years BP to 2750 cal. years BP, developed in the shadow of this coastal barrier.

The development of the coastal barrier is the thought to have been interrupted around 2200 years BP by human activity (Buen & Broquet, 1983). However, at prior to this at 2748 cal. years BP, a marine transgression was recorded by this research, followed by a further regression at 2654 cal. years BP. These events may well signify the start of barrier destabilisation at the Somme and the interruption described by Buen & Broquet (1983) could have simply represented barrier breaching. The sea-level index points obtained after 3000 cal. years BP at Estrébœuf, were validated using palaeoecological evidence, indicating that the last 1800 years BP has witnessed a series of two marine transgressions and regressions. The disappearance of the coastal barrier perhaps allowed the actual pattern of sea-level change to be observed.

The mid- to late-Holocene pattern of coastal evolution and sea-level change at the Somme, had already been partially explained by previous work undertaken on the coastal sediments. However, what has become apparent from the collection of new sea-level index points, validated using pollen, diatom and foraminifera, is that if a coastal barrier was present across the Somme between 6000 and 3000 years BP, its disturbance was probably the result of a transgressive event *c.* 2700 cal. years BP and not the result of human activity as previously thought (Buen & Broquet, 1983). Two dates collected as part of this research did fall within this period (dates 21 and 22 from BH SO8). The first pointed to a transgressive event *c.* 4800 cal.

years BP and the second to a regressive event *c.* 3750 cal. years BP. However, compaction of the sediment appears to have been a major problem, altering their altitudinal position by approximately 1m. In addition to this no palaeoecological data exists from which standardised water level indices could be obtained, thus the accurate palaeotidal level could not be established.

It is clear from the research undertaken at Estréboeuf and previous research, that the sea-level signal has been affected by the presence of a coastal barrier. A general rise throughout the mid- to late-Holocene period can been recorded and a rise above present day mean sea-level may have taken place *c.* 2700 cal. years BP. Elucidating the timings and rate of changes is complicated further by the extreme tidal range that the Somme currently experiences, which is up to 9m (Buen *et al.* 1998). If a high tidal range persisted throughout the Holocene, then past tidal levels can be established using present tidal information and a transfer-function. Spencer *et al.* (1998) showed that tidal range has remained constant over the past 6,000 years BP, and therefore presuming tidal range has not varied in the Somme Estuary is a valid assumption.

6.10 Conclusion

The pattern of sea-level change at the Canche clearly exhibits a pattern of steadily rising relative sea-level throughout the mid- to late-Holocene. A regional pattern can be detected when compared to other sites in northern France, with two main transgressions being recorded at c.3500 years BP and 2200 years BP. It is also apparent that the transgression at around 2200 years BP, recorded a high sea-level, however this did not appear to rise above present day mean level or MHWST, as previous research had suggested (Agache et al. 1963). A discussion of possible regional controls is presented in Chapter Four, and therefore is not repeated here. However, in this part of northern France changes in sediment flux appear to have been a major control on the formation of the dune systems (Antony, 2000). Thus, at the Canche and Somme the regional signals may have been controlled by changes in the convergence of sediment coming from the North Sea and the western coastline of France (Antony, 2000).

The fact that several high altitude index points are only recorded at the Canche indicates that a local force may have been responsible for producing these altitudes, possibly an increased tidal range. There is no evidence to support the presence of a coastal barrier at the Canche during the late-Holocene, however since much of the Picardie coastline was sheltered by a barrier (Buen & Broquet, 1983), it is possible that the Canche estuary was too.

The pattern of mid-to late-Holocene sea-level change at Estrébœuf revealed a number of relative movements. The earliest accepted marine transgression took place around 6300 cal. years BP. This was shortly followed by a marine regression *c.* 5700 - 5900 cal. years BP. Considerably later around 4800 cal. years BP a second marine transgression was recorded. Followed by a regression *c.* 3750 cal. BP. A series of transgressions then followed between 2700 cal. BP and 1700 cal. BP. The final sea-level index point was recorded around 1600 cal. years BP. A coastal barrier appears to have been in place during much of the late-Holocene complicating the pattern of coastal development. The study site at Estrébœuf appears to show that the small valleys contained in the estuary became fully blocked off from the sea between 6000 and 3000 years BP, however there is insufficient evidence to state whether the whole estuary was cut-off.

Chapter Seven Cross-channel comparison

The purpose of this chapter is to carry out a cross-channel comparison using previously published data and the data that have been collected as part of this research. Few attempts have been made to perform such a study (Delibrias & Morzadec-Kerfourn, 1975 and Heyworth & Kidson, 1982) and those that did tended to focus upon pre-existing data rather than collect new data with the intention of carrying out such a task. The investigation of mid- to late-Holocene sea-level change either side of the English Channel seems an obvious starting point when attempting to determine regional and local patterns of relative sea-level change, however past studies have avoided undertaking such comparative work due to the methodological problems encountered when examining inter-site variability. Thus, the collection and evaluation of new sea-level index points from either side of the English Channel offers an ideal opportunity to examine any variations in the timings of sea-level change. However, it must be acknowledged that the search for synchronous transgressions/regression is not simplistic. The issues, including both local and regional influences upon the pattern of sea-level change, involved in performing such a comparison are discussed later in this chapter.

7.1 Previous cross-channel comparisons

One of the earliest references to a cross-channel similarity was made by Delibrias & Morzadec-Kerfourn (1975). Although the research argued that a sea-level curve could not be presented for St-Michel, Brittany due to the compaction that was thought to have taken place, the pattern of relative sea-level change over the past 11000 years was thought to compare well with that of Godwin (1943) in Kent and Greensmith & Tucker (1973) in Essex.

However, the first attempt at a quantified cross-channel comparison was undertaken by Heyworth & Kidson (1982). Although, the paper focused on the errors that were involved in carrying out such a study when using previously published data and did not concentrate on the cross-channel results. However, it remains the only cross-channel sea-level curve to have been produced, based on the data of Delibrias & Morzadec-Kerfourn (1975).

Fig. 7.1 shows a sea-level curve for Bridgwater Bay and Cardigan Bay, SW England, which has been adjusted to MHSWT in St. Malo to allow comparison with the curve for the Bay of St. Michel, Brittany (Heyworth & Kidson, 1982). Once again the curves from south west England show a smooth gradually rising sea-level whereas the curves from St. Michel show a highly fluctuating sea-level that rose above NGF *c.*5500 radiocarbon years BP, declined below NGF at 2500 years BP and subsequently rose again over from 2000 years BP. The initial rise in sea-level is also seen to differ. Sites in England show evidence for a relative rise from *c.*9000 years BP, whereas sites in France do not reveal an *in-situ* sediments dating beyond *c.*8000 BP. However, if the fluctuations are removed , the general trend appears to compare well.

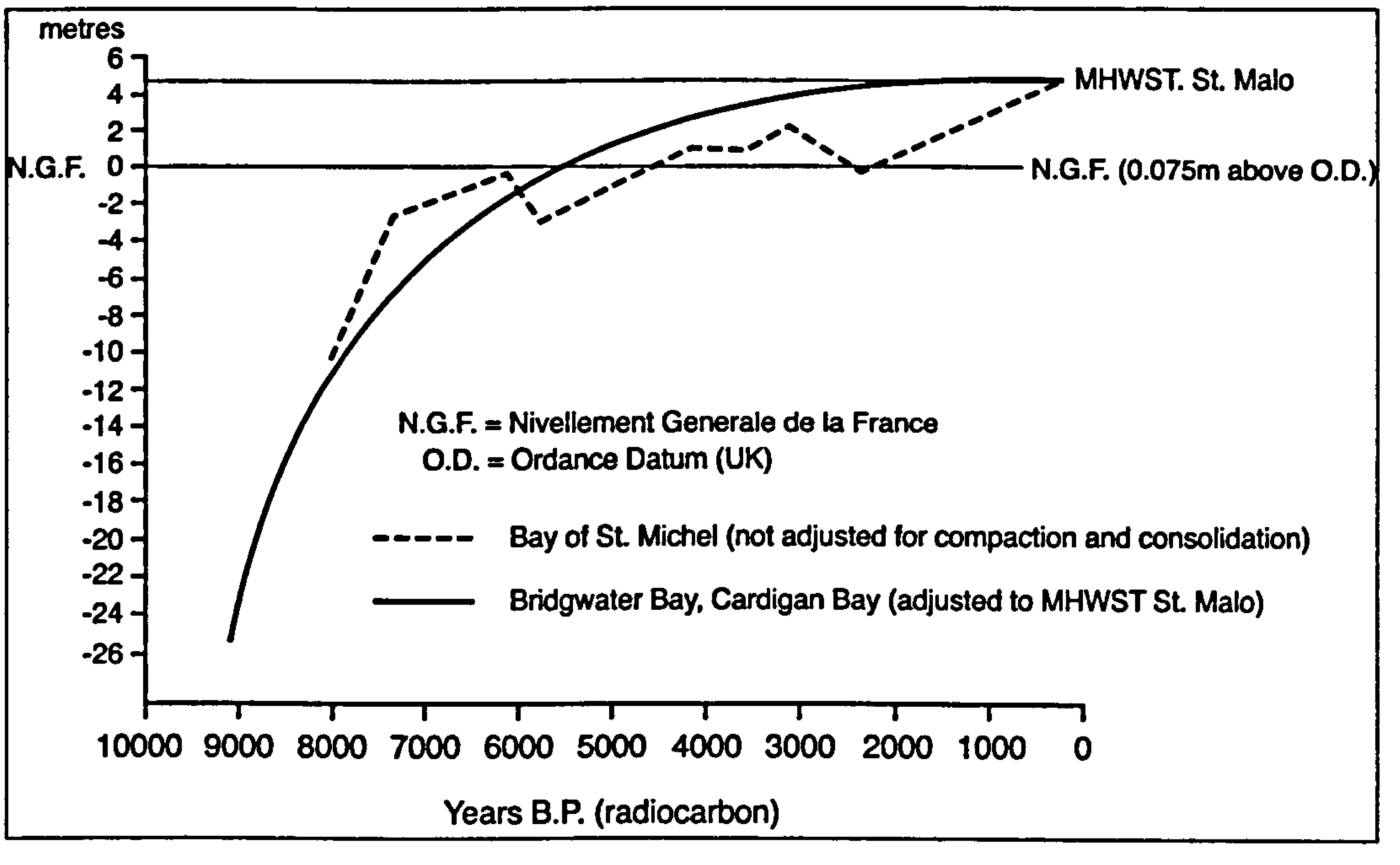


Fig. 7.1 Sea-level curves for the English Channel, Bristol Channel and Cardigan Bay (Heyworth & Kidson, 1982)

7.2 Cross-channel comparison using new and existing data

Once of the main difficulties encountered when undertaking a comparison between sites, results from the different methodologies that have been employed. Much of the original work on sea-level change in Britain and France relied upon the information provided from stratigraphic recordings and the fossil pollen record (Godwin, 1961; Mariette, 1971, Devoy, 1977; Ters, 1986). Although these studies provided information about the changes in sedimentation resulting from fluctuations in relative sea-level, past tidal levels could not be determined. Therefore, if a comprehensive comparison of the mid- to late-Holocene sea-level changes between south east England and northern France was to be performed, the collection of new sea-level index points based upon detailed stratigraphic and biostratigraphic evidence was essential. The use of a multi-proxy approach is now accepted as one of the most reliable methods of studying past sea-level changes. This means that much of the previously published work has been based on data that used a single-indicator to infer sea-level, which can often provide misleading findings and has to be excluded from comparative work. As previously discussed, the record of sea-level change over the Holocene has been complicated by changes in the tidal range (Austin, 1991) and by sediment compaction, and in the case of south east England, by barrier dynamics. Although an estimation of sedimentation is presented in this chapter, no attempt is made to account for changes in the tidal range. At present no reliable model of reconstructing palaeotidal level exists and this study is not an attempt to produce such a model. Therefore, the following comparisons exclude the possibility of variations in the tidal range over the Holocene.

Stratigraphic record

The pattern of mid- to late-Holocene sedimentation either side of the English Channel shows quite distinct differences. For example the deposits on the northern coast of France seem to be dominated by coarser material and exhibit a greater number of intercalated sediments. However, one similarity was the presence of a peat deposit at or around 0m OD/NGF, found at almost all the sites along the south coast of England and northern coast of France (Long & Innes, 1993; Jennings & Smyth, 1988; Ters, 1986 and Agache *et al.*, 1963). This could suggest that a regressive event, similar in altitude, had taken place either side of the Channel, but the age of the sediments would need to be compared.

The hard, oxidised upper silty clay found in the upper sediment units along the south coast of England was not present in the French sediments, being overlain by a sandy silty clay deposit. These upper sediments alone suggest that deposition had taken place under a much more storm influenced coastal environment, indicating that marine transgressions were still taking place. The range of sediment sizes found also indicated that the sediment may have been re-worked since its deposition, or that post-deposition human activity has altered the original pattern of sedimentation.

The pattern of sedimentation would suggest that sea-level change along the northern coast of France had exhibited a more fluctuating rising sea-level than that encountered along the south coast of England throughout the Holocene. This could be attributed to the increased tidal range experienced along the French coastline, > 9m at the Somme. A higher tidal range will result in exposure/submergence of sediments at higher/lower altitudes during high/low tide.

Pattern and timing of sea-level change either side of the English Channel: comparison between new data collected

Temporal comparison

The examination of regional trends in the temporal pattern of relative sea-level change is important as it can often provide essential information about the local, site-specific processes that have been responsible for controlling the pattern and rate of relative sea-level rise. Shennan (1987) found that by performing a regional analysis of relative sea-level curves, the local processes of crustal movement, tidal variations and local sediment consolidation can interact (p. 142). Thus, the performance of a cross-channel comparison is important in determining whether local or regional processes have been dominant in their control on the pattern and timing of relative sea-level rise.

The sea-level signals detected from the sites studied here all show a curvilinear rising sea-level curve over the past 10,000 years (see Fig. 7.2). The early changes in sea-level, between 10,000 and 6000 years BP, were characterised by a sharply rising sea-level (Ters, 1986). After 6000 years BP the data showed a more gently rising sea-level (see Figs. 4.8, 5.7 and 6.7), with both regressive and transgressive phases being recorded.

However, barrier dynamics complicate the sea-level signals at Pevensey and the Somme during this period. The final phase, post 2000 years BP, resulted in barrier breakdown, possible showing a increase in the rate of relative sea-level rise. The last 2000 years poses the most problems in south east England due to the lack of intercalated peat and silty clay deposits from which dated sea-level index points can be obtained. For example, the late-Holocene (last 2000 years) sediments at Romney Marsh, Kent are thought to have been deposited under a coastal setting but biostratigraphic records failed to produce reliable results (Plater *et al.*, 1999). These upper sediments were thought to be the result of an increase in storm events over the past 2000 years (Plater *et al.*, 1999). However, some research in France has produced reliable sea-level index points for the last 2000 years, which indicated that an increased rate of sea-level rise has taken place (refer to Table 7.2 after Ters, 1986; Agache *et al.*, 1963).

In Chapter Two, a tentative cross-channel comparison of previously published data discussed the similarities observed between some of the timings of the transgressive events (Table 2.15). The sea-level data that has been collected from the Pevensey Levels, the Canche and the Somme, improve the quality of the sea-level data by assigning indicative meanings to the sea-level regressive and transgressive overlaps and aid in carrying out a cross-channel comparison. This section will therefore be divided into two sub-sections, the first examining the differences between the field sites alone and the second will incorporate pre-published data with the findings from the study sites.

As discussed in Chapter Four, the results from the Pevensey Levels strongly indicated that the sediments that had been deposited following changes in coastal barrier dynamics. Therefore, only those dates post- 3500 cal. years BP recorded from the Pevensey Levels will be included in this comparison, the period believed to represent barrier destabilisation and breakdown. The sea-level signals detected at the Somme Estuary are also believed to have been influenced by coastal barrier dynamics, again complicating the comparison. In addition to this, since three of the AMS radiocarbon dates obtained from the deeper sediments at the Somme were thought to be invalid, only the inferred period of barrier destabilisation and breakdown, post 4000 cal. years BP, has been included.

Pre-4000 cal. years BP

A series of transgressive and regressive overlaps were recorded at the Canche and Somme estuaries prior to 4000 cal. years BP. The earliest dates that were obtained from the Somme cannot be accepted since two transgressive events and one regressive event were all indistinguishable once calibrated (*c.* 6800 cal. years BP), plus palaeoecological data was too sparse to base a sea-level interpretation on. The earliest accurately recorded regressive event at the study sites in northern France can be seen to take place around 5800 cal. years BP at the Somme and around 5500 cal. years BP at the Canche (see Table 7.1).

Pevensey Levels		Canche Estuary		Somme Estuary	
Transgression	**Regression**	**Transgression**	**Regression**	**Transgression**	**Regression**
					1700
				1800	
2200		2200			
					2600
		2800		2700	
3100		3200			
		3600			
	3700		3700		3700
3900			3900		
			5500		
					5800
					7000

Table 7.1 Sea-level transgressive and regressive phases either side of the English Channel

It can be seen from Fig. 7.2 that the data has not been adjusted to MHWST. At this stage in the interpretation the data are simply being presented relative to Ordnance Datum in order to illustrate the issues of interpretation more clearly. Data presented in Chapter Eight have been adjusted to MHWST.

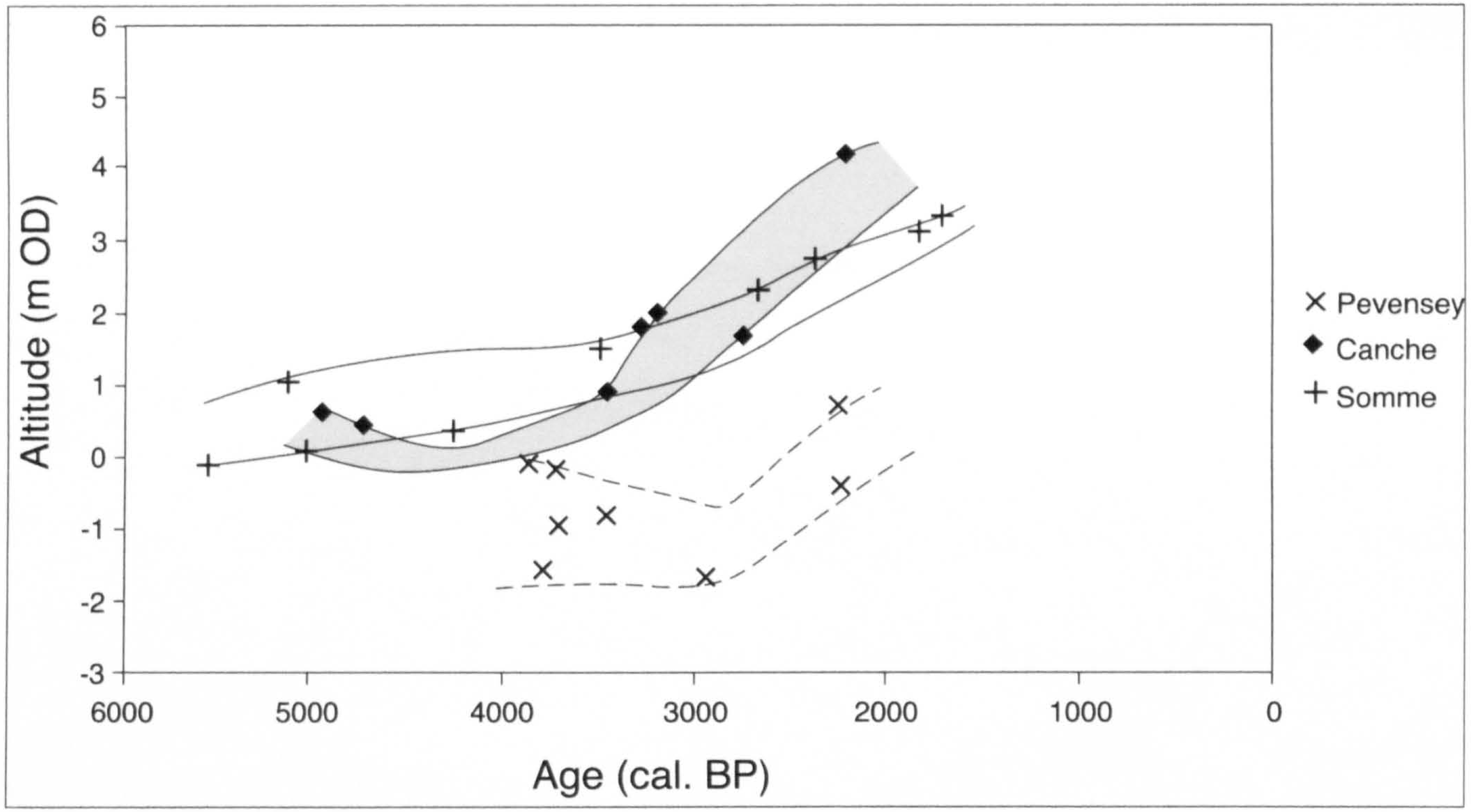


Fig. 7.2 Age-depth plot of sea-level index points from the Pevensey Levels, Canche Estuary and the Somme Estuary

Post-4000 cal. years BP

The onset of this phase at the Canche was marked by a regressive event *c.* 3900 cal. years BP, but no such event was detected at the Somme. At Pevensey, however, a transgressive event was recorded 3900 cal. years BP, possibly the result of barrier destabilisation and subsequent breakdown. This was followed at the Canche and Somme estuaries by a regressive event which took place *c.* 3700 cal. years BP. A similar event also appears to have taken place at Pevensey, with a regressive overlap dated to 3700 cal. years BP. This is the first indication that a similar fall in sea-level may have taken place either side of the Channel.

Several transgressive phases can then be seen to take place at the Canche, at 3600 cal. years BP, 3200 cal. years BP and 2800 cal. years BP. However, at the Somme only a single transgressive event took place around 2700 cal. years BP and at Pevensey too, *c.*3100 cal. years BP. In fact during this period at the Somme, a regressive event was recorded, shown by the presence of a peat deposit, during this time *c.* 2600 cal. years BP. This strengthens the claim that sedimentation at both the Pevensey Levels and at the Somme Estuary, was being controlled by the presence of a coastal barrier, most likely coupled with a fall in relative sea-level. The Canche Estuary clearly shows a period of rapidly rising sea-level between 3600 and 2800 cal. years BP, whereas the Pevensey Levels and the Somme Estuary were protected by the barrier system until 3100 cal. years BP at Pevensey and 2700 cal. years BP at the Somme.

A rise in relative sea-level can be seen either side of the English Channel around 2200 cal. years BP. At this time a transgressive episode was recorded at both Pevensey and the Canche, suggesting that a possible cross-channel event took place. However, since no evidence was provided for such an event at the Somme, it is not possible to state this with any certainty. What is possible to state is that by this time both the coastal barriers that had been dominating the coastal system at the three sites had now become destabilised. Therefore, both sites would not have been protected from a rising sea-level and the pattern of coastal sedimentation in the period post-2200 cal. years BP reflected this. It is possible that the event was not recorded at the Somme because the barrier was still allowing peat to form in its lee, thus affecting the sea-level signal.

As is a problem with much of the south coast of England, the upper sediments at Pevensey failed to produce any *in-situ* radiocarbon-datable material. The Canche Estuary also failed to provide any reliable sea-level signals younger than 2200 cal. years BP. However, the Somme appeared to show a transgressive event, slightly later, around 1800 cal. years BP and a possible final regression, 1700 cal. years BP, although evidence for this is relatively poor. The significance of these events is discussed in the following section, comparing the results to those of previous studies.

It can therefore be seen that some similarities in the timings of marine transgressive events can be seen either side of the English Channel indicating that a regional pattern of sea-level change during the mid- to late-Holocene period can be detected.

Altitudinal comparison

An altitudinal comparison of the transgressive and regressive can only reliably be undertaken if the sea-level index points have been corrected for compaction. In this section the estimates of compaction discussed in Chapters Four to Six are compared to one another in an attempt to identify any cross-channel similarities in the altitude of relative sea-level changes. It must be emphasised that the following section is based on estimations of compaction using Allen's (1999) exploratory equation for autocompaction. Detailed results may be found in Appendix IV. Fig. 7.3 presents an age-depth plot of sea-level index points corrected for estimated compaction. It must at this stage be noted that several problems arise when data are plotted relative to datum point rather than being corrected to MHWST. For example, variations in tidal range over time can not be accounted for. If data were to be adjusted to MHWST this would allow for these changes to be incorporated into the results. Results in Chapter Eight have been adjusted to MHWST.

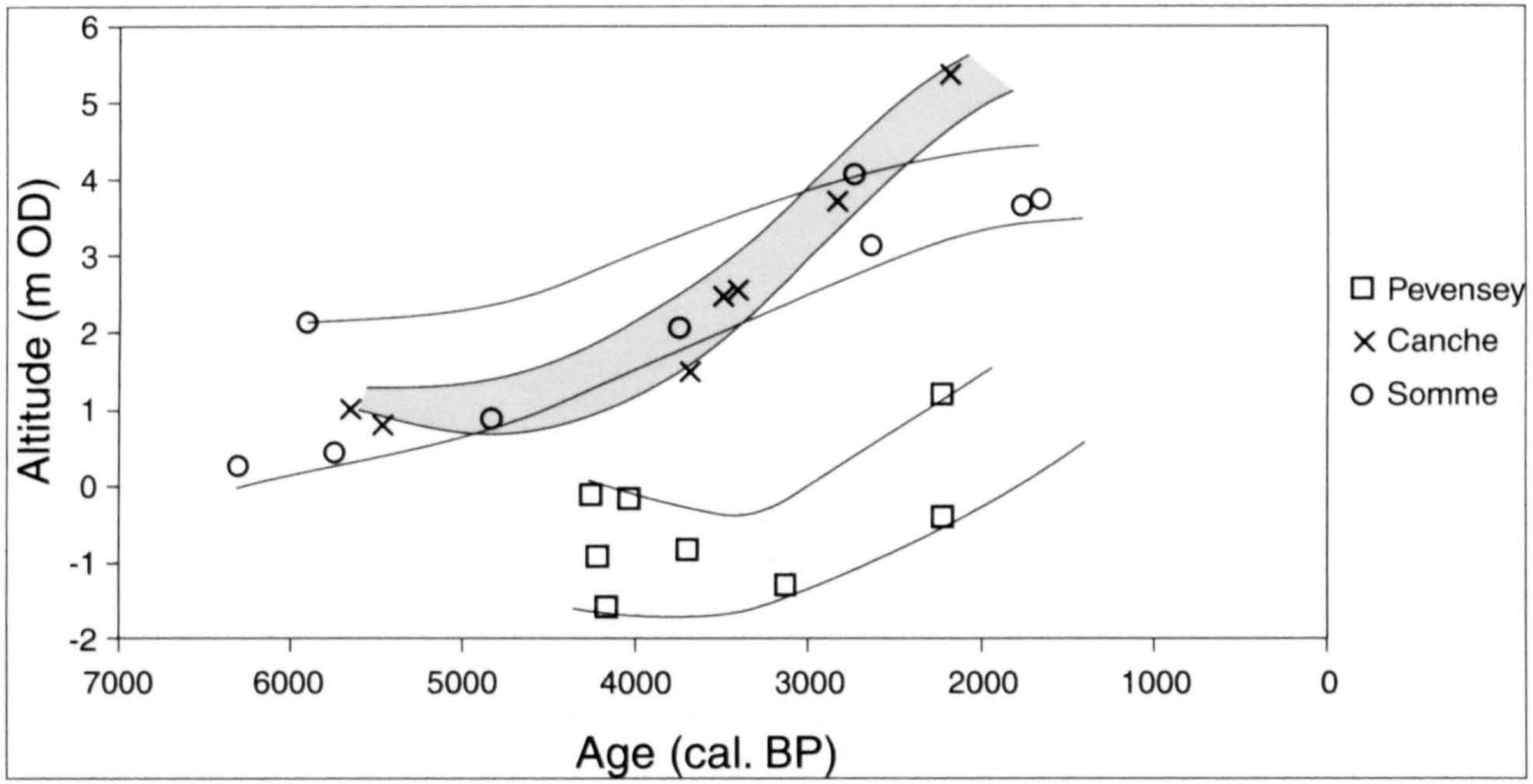


Fig. 7.3 An age-depth plot of sea-level index points from the Pevensey Levels, Canche Estuary and Somme Valley which have been corrected to allow for an estimate of sediment compaction calculated using Allen's (1999) exploratory model and presented relative to OD and not adjusted to MHWST.

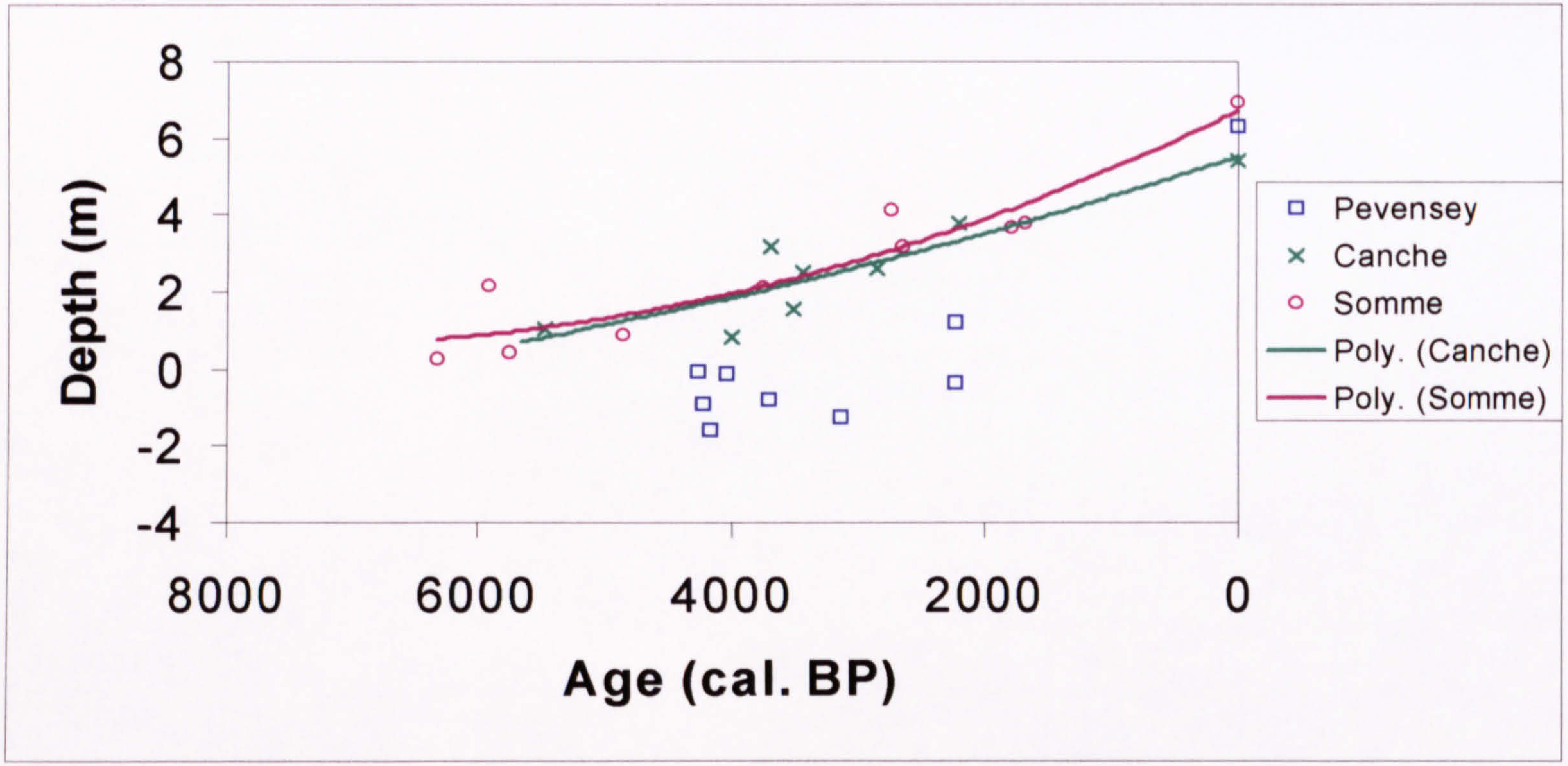


Fig. 7.4 An age-depth plot of estimated decompacted sea-level index points

(Including polynomial trend lines, which have been added to aid the comparison between data points).

Markers at zero indicated current MHWST at each sites

It can be seen in Fig. 7.3 that all the sea-level index points from France plot well above those collected from Pevensey. This is despite all the points being corrected to OD (all the sea-level index points from France have had 0.3788m added to their altitude). Few of the sea-level index points from the Canche or Somme show any altitudinal similarities, even when corrected for compaction of sediments. The points from the Canche plot above those collected from the Somme, possibly reflecting a variation in the tidal regime. It is also possible that these differences in altitude are indicative of differential crustal subsidence along the Channel coastlines. In northern France, the Canche lies to the north of the Somme and the variations in the altitude of the sea-level index points may indicate a north to south trend of land subsidence, with points in the north being less influenced than those in the south. When the French sites are compared to southern England, the differences between the altitudes of the data points also indicate differential land subsidence. It is well known that southern England is subsiding (Shennan, 1989) and the sea-level data from Pevensey seems to support the theory that south eastern England is subsiding at a faster rate than northern France. There also appears to be a south to north isostatic component affecting the coastline of northern France.

In Fig. 7.4 a polynomial trend line has been added (Shennan *et al.* 2000) in order to compare the gradient of the curves from each of the sites. The results from the Pevensey Levels indicated a gradient of 0.0065 but the R^2 value was only 0.438, indicating that the trend line did not fit the data points well. Therefore the line has not bee presented on Fig. 7.2.2.3. The addition of a polynomial trend line to the Canche results produced a gradient of 0.0041 with a more reliable R^2 value of 0.865. The trend line for the Somme revealed a gradient of 0.0009 with an R^2 value of 0.797, again showing a reasonable fit with the data. A comparison between the gradients of the trend lines shows a different pattern of Holocene relative sea-level change. The Pevensey Levels reveals a pattern of sea-level change at a lower altitude than at the Canche and Somme. The French sites also show a gradual, smooth rising relative sea-level, despite the biostratigraphic record showing a number of periods where the rise in relative sea-level was falling.

This comparison highlights the major differences observed either side of the Channel. Firstly, no points in south east England are found above +2m OD, whereas sea-level index points in northern France reach an altitude of +5m OD (corrected from NGF). Secondly, as already discussed, the sea-level index points collected from France produce an unlikely smoothly rising sea-level, when using only altitudinal data, than the points from south east England. Of course it must be remembered that the sea-level signal from Pevensey has been significantly affected by the presence of the coastal barrier.

Performing an altitudinal comparison between sea-level index points does not produce any cross-channel similarities, unlike the temporal comparison, which identified a number of similarities. Despite sea-level index points being corrected for an estimate of compaction and the difference between OD and NGF, the French results still plot 1–2 metres above those from south east England. Whether an altitudinal relationship can be observed once additional sites are included in the comparison is discussed later in the chapter.

Cross-channel comparison of new and existing sea-level data

The above discussion indicated that a number of similar sea-level changes could be seen to occur throughout the mid- to late-Holocene in south east England and northern France. The comparative table presented in Chapter Two (Table 2.16) also pointed to a number of similar events either side of the Channel. Once the new data collected from Pevensey, the Canche and the Somme has been included (see Table 7.2), these similarities become even more apparent.

The first feature to note is the mid-Holocene regression seen in Kent (Long & Innes, 1993), the French Channel coast (Agache *et al.* 1963) and at the Somme all at around 5500 C^{14} years BP. This appears to have been an important event across the Channel. In France and south west England it marks the beginning of a slowing rate of sea-level rise, following the rapid rise which took place between 10000 and 6000 cal. years BP (Mariette, 1971; Morzadec-Kerfourn, 1975 and Heyworth & Kidson, 1982). However in Sussex, Romney Marsh and the Canche Estuary, it can be seen that sea-level rise continued after 6000 years BP. This is an inconsistency previously noted between sites in south east England, with Romney Marsh and Sussex showing a continuing rise after this time and the East Kent Fens showing a slowing down in the rate of relative sea-level rise after 6000 years BP (Long, 1991).

At around 3200 cal. years BP, another major transgressive event appears to have occurred, which was recorded at both Romney Marsh and Pevensey, and along the Atlantic coast and Canche Estuary, although it took place slightly later at Pevensey *c.* 3100 cal. years BP. At

Pevensey this event marked the breaching of the coastal barrier that is thought to have dominated since *c.* 4000 cal. years BP. At Romney Marsh, this period 4000 to 3200 years BP was thought to be a phase of very rapid sea-level rise resulting in barrier breaching (Long & Innes, 1993; Spencer *et al.* 1998). At the Canche Estuary from *c.* 3500 to 2800 cal. years BP, three transgressive phases were recorded during this period, showing sea-level was still rising at this time. However, research along the Atlantic coast (Ters, 1987) only revealed a single transgressive event *c.* 3200 cal. years BP. Whether the transgressions represented the onset of rapid sea-level rise either side of the English Channel or whether they simply marked a change in the dynamics of the coastal barriers, allowing a change in the sediment influx, cannot be stated with any certainty. However, the fact that all these sites experienced a similar event between 2800 and 3200 cal. years BP suggests a regional transgressive event may have been recorded.

At around 2800 cal. years BP the data from Essex, Romney Marsh, the Canche and the Somme revealed that all four sites experienced another comparable marine transgression, although the timing of the Somme event was slightly later *c.* 2700 cal. years BP, but within the range of dating errors. In Essex, the sea-level at this time was believed to be 1.5m below the present day level (Greensmith & Tucker, 1973), and results indicated that Essex was experiencing a rapid rate of sea-level rise *c.* 2800 cal. years BP.

The final transgressive event that is evident either side of the Channel took place *c.* 2200 cal. years BP. At Romney Marsh and Pevensey, this marked the breakdown of the coastal barrier, allowing the areas to become inundated by the sea. This event was also the final transgressive event recorded at Pevensey; however at Romney Marsh there is evidence for a later transgressive event between 2800 and 1900 cal. yrs BP (Spencer *et al.*, 1998). However, a similar transgressive event was also seen to take place in France, at the Canche Estuary and along the Atlantic coast. Coastal barriers are not believed to have affected the sea-level signals obtained from the Canche and Atlantic coast, thus suggesting that the rise in sea-level experienced at this time could have been a Channel-wide event.

Age Range	Essex	Romney Marsh	Thames (Thames & Tilbury)	Lagney Point	Pevensey Levels	Brittany	French Channel coast	Atlantic coast (Calais & Dunkerque)	Canche Estuary	Somme Estuary
10000-9000										
9000-8500	8900			8770						
8500-8000			8200							
8000-7500	7500									
7500-7000						7000		7400		
7000-6500			6575							
6500-6000						6000	5800	6100		
6000-5500		5500								
5500-5000				5000				5000		5300
5000-4500						4500	4500			
4500-4000	4000						4300	4000		
4000-3500			3850		3900	3500				
3500-3000	3350	3200					3200	3200	3200	
		3000		3000	3100					
3000-2500	2800	2800	2600						2800	2700
2500-2000		2200		2200			2300	2200	2200	
		2100					2200			
2000-1500			1750				1900	1800		1800
1500-1000	1400							1100		
1000-0	300									

Table 7.2 Comparison between transgressive events either side of the English Channel (Based on data from Greensmith & Tucker, 1964; Mariette, 1971; Morzadec-Kerfourn, 1975; Devoy, 1979; Jennings, 1985; Ters, 1987; Long & Innes, 1993 plus results from the study sites Villiers and Estrébœuf)

A comparison between the sea-level curves based on age-depth points (Fig. 7.5) portrays quite a different picture. As previously discussed, such a comparison becomes subject to a number of inherent methodological problems and therefore only those studies which employed similar techniques have been chosen, and data from those has been limited to results from single sites (refer to Chapters Five and Six). Therefore the comparative age-depth plot (Fig. 7.5) contains data based on depth in metres OD, with those points based on depth in metres NGF corrected to OD (OD is 0.3788m higher than NGF). Only points taken from peat contacts have been included and the data can therefore be assumed to represent deposition at MHWST. Performing an altitudinal comparison using new and existing data from south east England and northern France cannot be undertaken. Data from existing studies have not been corrected for compaction and therefore cannot be compared to corrected data from the study sites. For this reason, all data referred to is based on uncorrected altitudinal data.

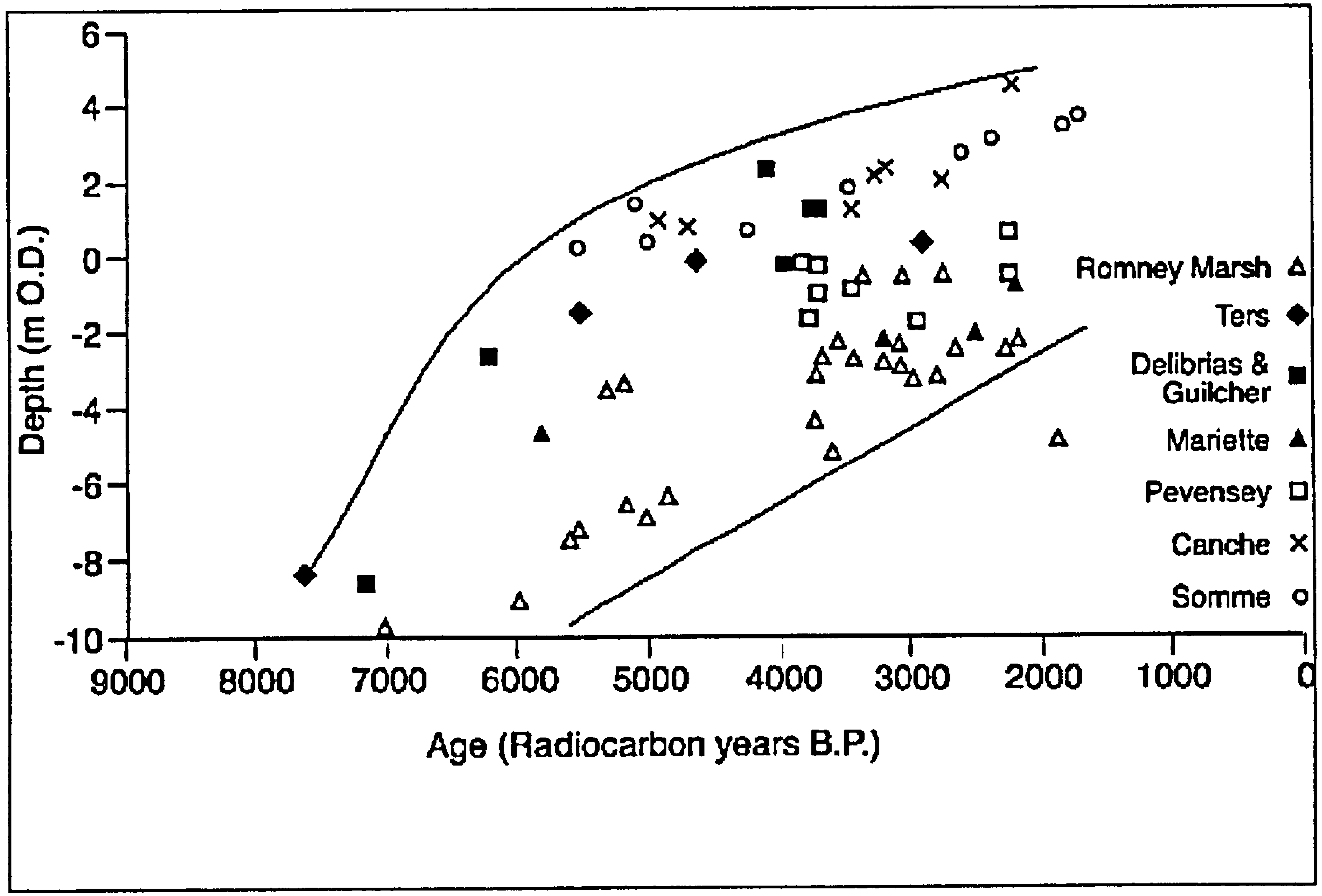


Fig. 7.5 Age-depth plot of sea-level changes either side of the English Channel. All points corrected to m OD but not adjusted to MHWST.

After: Mariette (1971) Brittany coast; Delibrias & Guilcher (1971); Atlantic and Channel coast; Ters *et al.* (1980) Atlantic coast; Long & Innes (1993) Romney Marsh and the data collected from the Pevensey Levels, Canche Estuary and Somme Estuary

Similar transgressive overlaps have also been recorded either side of the Channel at around 3200 years BP. If the altitudes of these data points are compared, a marked difference can be observed. At the Pevensey Levels a transgressive overlap was recorded 3100 years BP at around –1.64m OD. At Romney a similar event was also recorded 3200 years BP at an altitude of approximately –2.0m OD. However, on the other side of the Channel, transgressive overlaps were recorded at a similar time *c.* 3200 years BP, but Mariette (1971) presented an altitude of –2.10m OD (corrected), Ters *et al.* (1980) recorded the event at an altitude of +0.50m OD (corrected) and this study recorded the transgressive overlap 3200 years BP at an altitude of +2.25m OD (corrected). It can therefore be seen that performing comparison based solely upon stratigraphic and altitudinal data could provide quite misleading results.

Once again the French sea-level curves plot higher than the English; however there is no clear evidence that sea-level has ever risen above current MSL or MHWST. The work carried out at the Canche and Somme did show very high sea-level index points, but none were higher than the reference water level MHWST. There are several possible explanations for why the data from France plot above that from south east England. Firstly, this could be explained by examining the differential crustal subsidence between the two regions (refer to Fig. 2.7 Shennan, 1989), as previously discussed. The second possible explanation is that the sediments have been subjected to differential compaction. Sediments will have compacted under self-weight, autocompaction. The lower clay units present in south east England are likely to have experienced more autocompaction than the sand units present in the lower sediments in France. Thus, partly explaining why the points in south east England would plot below those in France. However, the extensive sand units which dominate the upper sediments in France would have caused compaction of the sediments below. However, as previously discussed because compaction rates for sand were not included in the exploratory model (refer to previous chapters) developed by Allen (1999) it has not been possible to quantify sediment compaction accurately.

The final explanation for this could be the difference in tidal range between the French and English sites. At the Pevensey Levels the tidal range is 8m, compared to up to 9m at the French sites. This could explain the difference between the altitudes of the sea-level index points seen in Fig. 7.5. If data were to be adjusted to MHWST, as has been done in Chapter Eight, the difference between the data points would be reduced.

Of these explanations presented, differential subsidence appears to be most likely to have caused the French data points to plot above those from south east England. Sites in south eastern England appear to have been more affected by subsidence of the land, than the sites in northern France. Although little data exists on the pattern of differential crustal movement for the northern coast of France, as it is thought to be too complicated to produce a generalised pattern (Ters, 1986), it can be seen that the sites in the south show more signs of subsidence that the sites in the north. The altitudinal difference between the south east coast of England and the northern coast of France could also reflect this, since sites in south east England have clearly subsided more than sites in northern France.

The findings of the altitudinal comparison casts doubt over the accuracy of the previous sea-level curves produced for the French coasts, since many of the points used to construct the relative sea-level curves were not reliable sea-level index points. Without an indicative range and meaning being assigned to a dated point, past tidal level can not be determined and therefore conclusions based upon mainly stratigraphic and palynological changes must be subject to further analysis.

Evidence is also present here which proves that the 3-5m amplitude oscillations recorded by Ters (1973) were the result of methodological errors. Ters (1973) used data taken from a number of sites along the French Atlantic and Channel coasts and combined them to create a single sea-level curve. Examination of the data in Chapters Five and Six also showed these oscillations to be unreal, confirming the findings of Lambeck (1997). Differential compaction of sediments taken from different cores and variations in tidal regimes between the difference estuaries alters the altitude of the peat surface, causing major fluctuations in relative sea-level rise to appear. In fact, if only single sites are used there is no evidence for these fluctuations, especially at the scale that Ters (1973) suggests.

The examination of the timings of the transgressive events either side of the English Channel does reveal a number of similarities. However, as can be seen in Table 7.2, there are also a number of transgressive events that are only seen at the estuary-sized scale. While it may be possible that at least two large-scale mid- to late-Holocene transgressive events have been detected, *c.* 5000 cal. years BP and *c.* 2200 cal years BP, it appears that the most dominant control upon the pattern of coastal sedimentation at the sites examined has been local coastal factors. Local forces such as changes in tidal regime and coastal barrier dynamics have exerted a significant control upon all the coastlines examined as part of this research. What becomes apparent when a comparative study across a large area is undertaken is that similar events can be recognised, however producing a generalised pattern of sea-level change is not possible.

7.3 Comparison between Romney Marsh, the Pevensey Levels and the Somme

Local coastal forces coupled with regional sea-level changes appear to have controlled the pattern of coastal sedimentation at the sites discussed above. At three of these sites (Romney Marsh, Pevensey Levels and Somme Estuary) the dominant factor was the presence of a coastal barrier throughout much of the mid- to late-Holocene period. Closer examination of the timings and pattern of barrier initiation, stabilisation and breakdown show a notable cross-channel similarity, in particular between the Pevensey Levels and the Somme (Table 7.3).

	Barrier Initiation	Barrier Stabilisation	Barrier Breakdown
Romney Marsh	6000-5000 yr BP	5000-2000 yr BP	2000-present
Pevensey Levels	4000 yr BP	4000-3000 yr BP	3000
Somme Estuary	6000 yr BP	6000-3000 yr BP	3000-present

Table 7.3 Summary of coastal barrier development either side of the English Channel (Romney Marsh data based on Long & Innes, 1993)

Table 7.3 clearly shows that barrier extension and stabilisation was possible during the mid-Holocene in both south east England and northern France. This suggests that following the early-Holocene period of rapid sea-level rise, a fall in the rate of relative sea-level rise had been experienced on both sides of the Channel. In order for a coastal barrier to exist, firstly it would require a supply of sediment, which in the case of the three sites above, appears to come from off-shore (Jennings & Smyth, 1987). Secondly, it would require a coastal setting which would not hinder its development. Therefore, throughout the mid-Holocene, the net rate of sea-level rise must have been relatively low. In order for a coastal barrier to de-stabilise, there must either be a change in the barrier dynamics, such as breakdown resulting from increased storm activity causing continuous overwash or a rise in sea-level. Following the breakdown of these barriers, the rate of relative sea-level rise must have either fallen once more, or a change in sediment supply has occurred, allowing sediment accretion and the development of a salt marsh *c.* 3000 cal. years BP, seen at both the Somme and the Pevensey Levels.

7.4 Conclusion

The cross-channel comparison undertaken as part of this research has highlighted the need for inter-site studies to be carried out using the same methodological techniques. Establishing the pattern of sea-level change either side of the English Channel using the data collected from Pevensey, the Canche and the Somme, allowed a more straightforward comparison to be undertaken. As shown by the discussion, attempting such a comparison using existing data alone should be avoided, unless significant additional biostratigraphic research is performed first and data is corrected to common references e.g. reference water level. The study has also highlighted the need for the development of a diatom or foraminiferal-based transfer function for northern France, in order to allow a quantitative comparative study to be undertaken. This will require the production of a good contemporary training set from south east England and northern France.

The comparison between sites including interaction between local coastal barrier dynamics and channel-wide relative sea-level change highlights the complexity of the mid- to late-Holocene rise in relative sea-level. Distinct periods of falling rates can be observed from around 5000 years BP, followed by a period of enhanced sea-level rise, promoting the theory for barrier de-stabilisation and breakdown around 2000 years BP. The final period was characterised by a subsequent fall in the rate of relative rise.

There is a clear regional temporal pattern of Holocene sea-level change either side of the Channel, however an altitudinal comparison of the data revealed significant differences. It is clear that local and regional controls have altered the pattern of coastal development either side of the English Channel and affected the sea-level signals. Several possible controls can be identified. A change in the influx of sediment into the English Channel (Antony, 2000) could have caused barrier instability. A reduction in the supply of sediment could have resulted in the breakdown of the barrier. At a more regional scale, a change in climate could have taken place. At around 2800 years ago there was believed to be an increase in wetness in Britain. Increase in storms could have resulted in flooding of the peat as seen at Romney Marsh (Spencer *et al.*, 1998).

The cross-channel comparison leads to the conclusion that determining a generalised pattern of cross-channel sea-level change throughout the late-Holocene should not be attempted.

Studies should only be undertaken at the estuary-sized scale, with no attempt to produce sea-level curves at the regional scale. However, this does not mean that regional comparisons are ineffective. Their importance in determining whether local or regional effect has been dominant, warrants performing such comparisons.

Chapter Eight Geophysical modelling

8.1 Introduction

The observational sea-level data collected from the sites at the Pevensey Levels, East Sussex and the Canche and Somme Estuaries, northern France, have provided diverse results. As discussed in Chapter Two, the collection of multi-proxy observational data is just one method available with which to study sea-level change. In recent years geophysical models of relative sea-level change has allowed research into the pattern and timing of Holocene sea-level change to advance. However, the differences between the observational and the modelled data highlight the need for an increased amount of observational data from a greater number of sites to be incorporated into the model.

The model developed by Lambeck (1990, 1993 and 1997) was chosen as the comparative model in this research for several reasons. Firstly, the modelled data showed a reasonable agreement between observed and predicted sea-level data for far-field sites in northern Europe (sites that were not covered by an ice sheet or sites that are away from the margins of past ice sheets) for the past 6000 years (Lambeck *et al.* 1990). Secondly, the model was calibrated using sites either side of the English Channel (Lambeck, 1993, 1997). Thirdly, Lambeck (1993) stressed the importance of using small-scale sites to reconstruct past changes in sea-level and the sites used here will add to the increase the amount of data available. Lastly, the observational data that had been used from sites in France was criticised by Lambeck (1997) for being too varied, being based on archaeological, shell-bed and mollusc information, which "do not provide clear indicators of sea-level position" (Lambeck, 1997 p.13). Much of the data previously collected in France therefore could not be used, leaving only those studies which had used freshwater and brackish peat overlaps to determine the pattern of sea-level, many of which had little or no palaeoecological data associated with them.

Of the sites in Britain that Lambeck used to constrain the model (1993 and 1997), the only south east England site to be included was the Thames Estuary. Therefore, the aim here is to test further data from south east England, by using both observed and predicted results from the Pevensey Levels. In France, the Somme had been included (Lambeck,

1997) but as discussed in Chapter Two, the data obtained from these studies was unreliable.

8.2 Parameters used in modelling sea-level data

Previous comparative studies have shown that a number of inherent problems are encountered when trying to compare observational and predicted data (Shennan *et al.* 2000). However, before the outcome of the observed-versus-predicted sea-level results are discussed, the parameters used in the model need to be reviewed.

The details of the model used to calculate the predictions for the study sites are contained in Chapter Three and are therefore not discussed here. However, it is important to describe some of the parameters, which are relevant to the study sites on the French Channel coast in particular, in more detail. The earth model applied to the French sites by Lambeck (1997) was based upon the model developed by Lambeck *et al.* (1996). It was assumed that Britain and France had a similar tectonic setting and, therefore, their mantle parameters were likely to be the same. This assumption enabled Lambeck (1997) to use an inversion of the sea-level data collected to determine the lithospheric thickness component of the equation (see Chapter Three). For the ice-model element, Lambeck (1997) had to infer the ice thickness term, because the sites involved were far-field locations. Thus, an inversion of the sea-level data from Scandinavia was used. However, this resulted in several inherent problems being encountered due to the fact that a near-field site was used to infer a value for a far-field site. Firstly, the use of the Scandinavian data lowered the amplitude of maximum sea-level and secondly, the data led to a delay in the timing of the maximum sea-level.

The remaining parameters introduce errors that apply to both observed and predicted studies of sea-level change. The use of radiocarbon dating involves a significant error, usually represented by the one-sigma and two-sigma error terms on sea-level curves produced using observational data, but these errors are not included in predicted data. Furthermore, the errors that are introduced through compaction and consolidation of the sediments will vary between sites, depending on the type of sediments present. In the research undertaken along the French Atlantic and Channel coasts, Lambeck (1997) had to assume that sediment compaction had not been significant, and the compaction error was assumed to have been 1m. The sites were also assumed to be tectonically stable and the isostatic response was calculated to have been 1-2mm yr^{-1}, however work by Shennan (1989) revealed far more diverse results, including negative isostatic values for southern England.

A significant error also exists when incorporating tidal range into the data, a factor that is more difficult to make a generalisation about, and needs to be calculated on an individual site basis. Present tidal range in the Somme Estuary is up to 9m (Anthony, 2000) and at Pevensey it is approximately 8m. Tidal range along the French Channel coasts is known to have varied during the Holocene (Shennan *et al.,* 2000a); however quantifying this change required the development of a tidal model (Lambeck, 1997). Lambeck (1997) assigned a tidal error for brackish-water peats of 1.5 to 2.5m, but for the last 6000 years it was assumed a tidal error of 1m.

Finally, before observed and predicted data can be compared, the results need to be corrected to mean sea-level. Observational data represents deposition at or around MHWST, thus, in order to allow for tidal effects observational data must be adjusted to MTL. Shennan (1986b) suggested that observational data should be corrected by reducing the altitudes of the sea-level index points assuming the following. Phragmites/ monocotyledonous peat overlying saltmarsh mud is equal to m^1 - 20cm (where m^1 is (HAT+MHWST)/2). Phragmites/monocotyledonous peat underlying saltmarsh mud is equal to MHWST. Fen wood peat overlying saltmarsh mud is equal to m^1. Fen wood peat underlying saltmarsh mud is equal to MHWST. This clearly involves a number of assumptions. Firstly, it assumes it is possible to identify the origin of the peat deposit through biostratigraphical data. Secondly, the method assumed that tidal range has remained constant over time, which is known to be incorrect (Shennan *et al.* 2000a). The first of these is of particular importance since for many sites, especially the French sties, biostratigraphical data is sparse, making the identification of palaeo-tidal level more difficult.

The discussion that follows is based upon the predicted results supplied by Lambeck (*pers. comm.* 2002) for each of the study sites. A number of corrective terms have been incorporated into the observational data since it is an integral part of the study. However, it must be remembered that many of these corrective terms are based on assumptions and have not been quantified using observational data.

8.3 Comparison between observed and predicted sea-levels at Pevensey

The data collected from the Pevensey Levels has been plotted against the predicted data (Fig. 8.1). In each of the diagrams a sea-level band has been added to aid the comparison and show more clearly the minimum and maximum index points. As previously discussed in Chapter Four, the sea-level record from the Pevensey Levels has been complicated by the presence of a coastal barrier throughout the mid-Holocene. Therefore, those points not believed to represent sea-level index points have been excluded from the comparison. Fig. 8.1 presents the uncorrected observational data from the Pevensey Levels plotted against the predicted data calculated by Lambeck. There are clear differences between the observed and predicted data. The observed data clearly exhibits a period when the area was not under marine influence, whereas the modelled data exhibits a smooth continuously rising sea-level throughout this period. The gradients of the curves are also quite different, with the observed data showing a sharper gradient than the predicted data. The observational data also exhibits a greater spread compared to the predicted data.

It is also clear from the graph that most of the observed data points from Pevensey plot above the predicted points. A similar outcome was noted by Lambeck (1993), who stated; "... for the sites in Wales, southern England and the French Channel coast, the predicted sea-levels are generally consistent with the observations, although at a number of sites the observations lie above the predicted level." (Lambeck, 1993 p.984). The reason for this difference include the fact that each observed data point is plotted relative to OD, irrespective of indicative meaning, whereas Lambeck plots points using MSL as the reference water level. Also, the observed points have not been corrected for compaction. If an accurate comparison is to be carried out, the observational data points need to be corrected to MSL.

In Fig. 8.2 the sea-level index points have been reduced from MHWST to MTL using the methodology of Shennan (1986b). The palaeoecological data were used to determine whether a peat was a transgressive or regressive overlap and corrections were made based upon Shennan (1986b). At Pevensey MHWST is 6.3m, MHW is 5.75m and MTL is 3.4m. Table 8.1 presents the corrections that have been made to each sea-level index point.

Clear differences can be seen once the data points are corrected to mean sea-level (MSL/MTL) (Fig. 8.2). Firstly, the observed data once reduced to MSL now lie well below the predicted data, indicating that the model over-estimates the relative sea-level rise. The difference between the observed and predicted data ranges from 3m *c.* 3000 BP to just less than 1m *c.* 2000 BP. This suggests that the data are more comparable for the late Holocene than for the mid-Holocene.

The second difference to note is that the clustering of the index points recorded by the observational data can still be seen, whereas the predicted data continues to show a smoothly rising sea-level curve. However, because this clustering is believed to be the result of barrier dynamics throughout the mid-Holocene, the predicted data would not be expected to reveal the same pattern, and there will therefore, always be a difference between the observed and predicted pattern of sea-level change for the period 4000-2000 cal. yrs BP.

An estimate of compaction has been made for the sea-level index points from Pevensey (refer to Chapter Four), and therefore it is necessary to incorporate this correction into the comparison. The application of a 1m-compaction error was included in the model; however, how this figure was reached was not fully explained (Lambeck, 1997). By using the estimates of compaction obtained for each sea-level index point at Pevensey based on Allen's (1999) exploratory model, it can be seen that for two of the index points their positions are raised by almost 0.5m (Fig. 8.3). However, due to the nature of the sediments and the equation employed it was not possible to correct all the data points and thus errors will exist in the data. It can be seen in Fig. 8.3 that by incorporating an estimate of compaction, the altitudes of the observational sea-level index points are raised, thus, reducing the difference between the observed and predicted data further. For the sea-level index points dated *c.* 2200 cal. yrs. BP the difference was reduced to only 0.5m, indicating a good agreement between the observed and predicted data. Once again there is a difference between the pattern and gradient of the two sea-level curves due to the influence of barrier dynamics throughout the mid-Holocene at the Pevensey Levels.

Type of overlap	Original altitude (m)	Radiocarbon Age (cal. yrs BP)	Correction required	Difference between correction and MTL	Corrected altitude (m)
Transgressive	0.73	2218	MHWS-20cm 6.3-0.20 = 6.10	6.10-3.4 = 2.7	0.73 – 2.7 = **- 1.97**
Transgressive	-0.37	2221	MHWST-20cm 6.3-0.20 = 6.10	6.10-3.4 = 2.7	-0.37 – 2.7 = **- 3.07**
Transgressive	-1.64	3129	MHWST-20cm 6.3-0.20 = 6.10	6.10-3.4 = 2.7	-1.64 – 2.7 = **- 4.34**
Regressive	-0.81	3694	m^1 – 20cm 7.20-0.20 = 7.0	7.0 – 3.4 = 3.6	-0.81 – 3.6 = **-4.41**
Regressive	-0.15	4025	m^1 – 20cm 7.20-0.20 = 7.0	7.0 – 3.4 = 3.6	-0.15 – 3.6 = **-3.75**
Regressive	-1.58	4149	m^1 – 20cm 7.20-0.20 = 7.0	7.0 – 3.4 = 3.6	-1.58 – 3.6 = **-5.18**
Regressive	-0.91	4027	m^1 – 20cm 7.20-0.20 = 7.0	7.0 – 3.4 = 3.6	-0.91 – 3.6 = **-4.51**
Regressive	-0.07	4254	m^1 – 20cm 7.20-0.20 = 7.0	7.0 – 3.4 = 3.6	-0.07 – 3.6 = **-3.67**

Table 8.1 Corrections made to mean sea-level for index points collected from Pevensey based on Shennan (1986b) and Lambeck (1997). Tidal data is based upon Admiralty tide tables 2001. Where m^1 = (HAT+MHWST)/2 = 7.20m

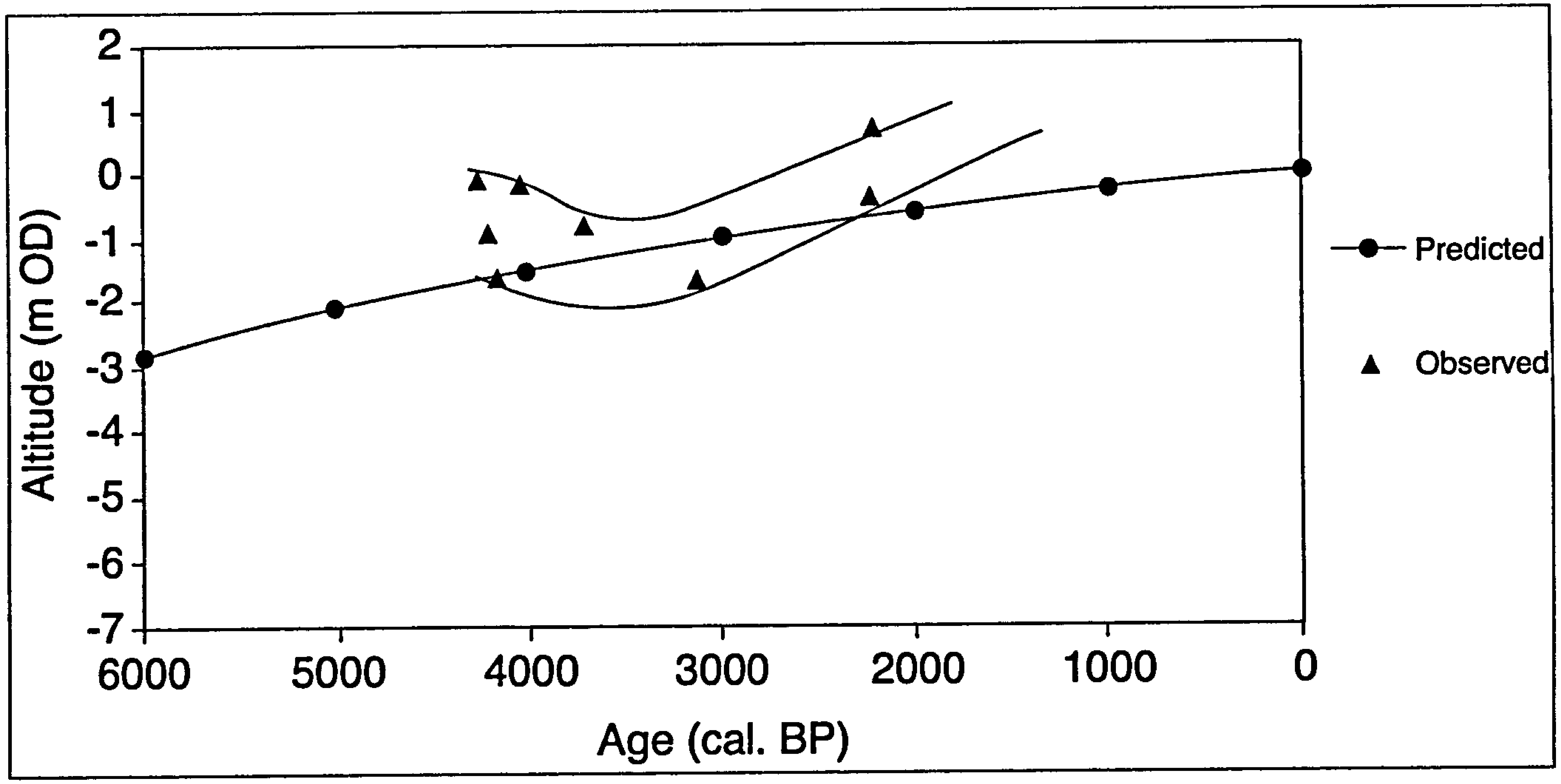


Fig. 8.1 Observed (uncorrected) sea-level data (▲) plotted against predicted sea-level data (•) for the Pevensey Levels, East Sussex. The observed data has not been connected by a line, because no apparent relationship between age and depth could be established due to the presence of a coastal barrier at the time of sediment deposition. A sea-level band has been added to aid the comparison between the observed and predicted data.

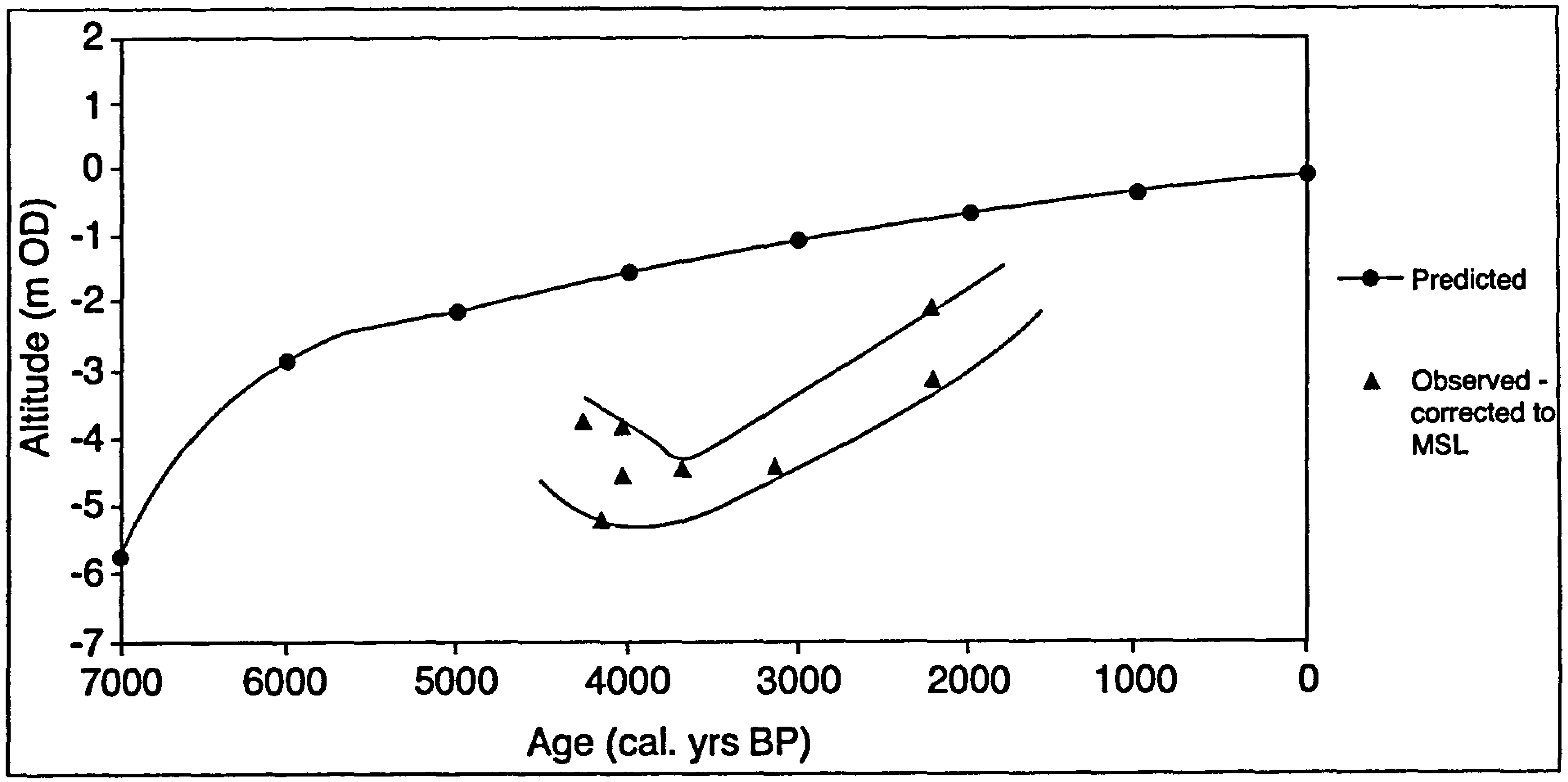


Fig. 8.2 Comparison between observed data corrected to MSL (▲) and predicted data (●) for the Pevensey Levels. A sea-level band has been added to aid the comparison between the observed and predicted data.

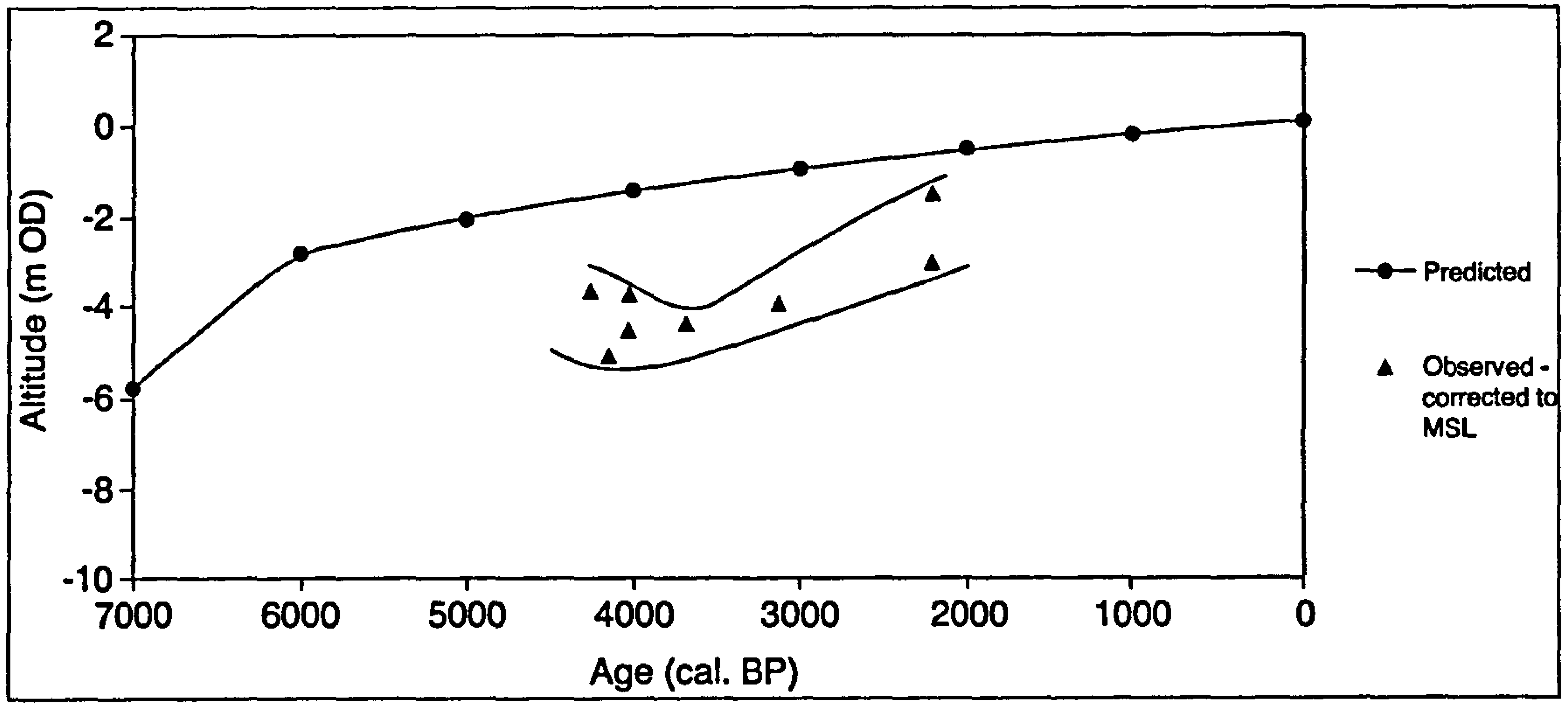


Fig. 8.3 Observed data reduced to MSL and corrected for an estimate of compaction (▲) plotted against predicted data (●) for the Pevensey Levels. Compaction estimate is based on the model proposed by Allen (1999). A sea-level band has been added to aid the comparison between the observed and predicted data.

8.4 Comparisons between observed and predicted sea-levels at the Canche Estuary

The general pattern of observed sea-level data over the last 6000 years showed close agreement with that predicted by Lambeck (*pers. comm.*), but once again it can be seen that the uncorrected observed data lie above the predicted data (Fig. 8.4). At the Canche MHWST is 7.18 and MTL is 5.07.

Type of overlap	Original altitude (m)	Radiocarbon Age (cal. yrs BP)	Correction required	Difference between correction and MTL	Corrected altitude (m)
Transgressive	4.20	2207	MHWST – 20cm 7.18 – 0.20 = 6.98	6.98 – 5.07 = 1.91	4.20-1.91 = **2.29**
Transgressive	1.72	2851	MHWST – 20cm 7.18 – 0.20 = 6.98	6.98 – 5.07 = 1.91	1.72 – 1.91 = **-0.19**
Transgressive	2.01	3430	MHWST – 20cm 7.18 – 0.20 = 6.98	6.98 – 5.07 = 1.91	2.01 – 1.91 = **0.10**
Regressive	1.84	3508	m^1 – 20cm 8.79 – 0.20 = 8.59	8.59 – 5.07 = 3.52	1.84 – 3.52 = **-1.68**
Transgressive	0.92	3692	MHWST – 20cm 7.18 – 0.20 = 6.98	6.98 – 5.07 = 1.91	0.92 – 1.91 = **-0.99**
Regressive	2.80	3982	m^1 – 20cm 8.79 – 0.20 = 8.59	8.59 – 5.07 = 3.52	2.80 – 3.52 = **-0.72**
Regressive	0.45	5468	m^1 – 20cm 8.79 – 0.20 = 8.59	8.59 – 5.07 = 3.52	0.45 – 3.52 = **-3.07**
Regressive	0.64	5652	m^1 – 20cm 8.79 – 0.20 = 8.59	8.59 – 5.07 = 3.52	0.64 – 3.52 = **-2.88**

Table 8.2 Reductions to sea-level index points from MHWST to MSL at the Canche. m^1 = (HAT+MHWST)/2 = 8.79.Tidal data was provided by SHOM (2002).

Before any corrections to the observed data were made, the predicted data under-estimated the rate of sea-level rise (Fig. 8.4). The observed and predicted curves exhibited a similar gradient, but with the observed data being recorded at a higher altitude. The observed data also shows a larger range of altitudes than the predicted data which shows a smoothly rising sea-level curve. This wide range of altitudes is highlighted by the width of the sea-level band which has been added. Despite the obvious differences in altitude between the observed and predicted data, they do show a fairly close agreement, in particular in the gradients of their curves.

Once the correction to MSL is applied (Fig. 8.5), a much closer agreement between the observed and predicted data, with one of the observed data points lying on the predicted data curve (*c.* 3700 cal. yrs BP). A sea-level band has been added, with one lying slightly outside the range *c.* 3500 cal. yrs BP.

The application of the compaction term resulted in a slight increase in the difference between the observed and predicted data but on a broad scale the data are still comparable. It can be seen in Fig. 8.6 that the lowest index point has been excluded from the sea-level band as it seemed too low and no compaction correction, which would raise the point, could be established. The correction for compaction of the remaining sea-level index points caused a wide range of altitudes, resulting in a range of differences between the observed and predicted data when the points are studied in detail. The smallest difference recorded was 0.5m at around 3800 cal. BP and the largest difference recorded was 3m at around 2200 cal. BP. However, these differences could have been due to the estimates of sediment compaction that had been made, rather than actual discrepancies between the modelled and observed data. Once again corrections could not be performed on all of the data points due to the nature of the sediments and the compaction term which was employed. Possible explanations for the differences between the data are discussed further in section 8.6.

8.5 Comparison between observed and predicted sea-level at the Somme Estuary

The observed data from the Somme Estuary has been plotted against the predicted data compiled by Lambeck (*pers. comm.*) and once again it can be seen that the observed data lie above the predicted data (Fig. 8.7). The only similarity between the uncorrected observed data and the modelled data is that their gradients are alike. The lowest three sea-level index points have been excluded from this comparison because the palaeoecological and radiocarbon data (refer to Chapter Six) proved inconclusive and clear marine transgressions could not be identified.

As with the previous data, the observed samples need to be corrected to mean sea-level (see Table 8.3). The effect of this correction upon the observed data (Fig. 8.8) was a lowering of the points. This reduced the difference between the observed data and the predicted data significantly, producing a close match between the data sets. Once again the addition of a sea-level envelope to the corrected data helps to show the close similarity between the observed and predicted results, with a gently rising sea-level curve being seen throughout the mid to late Holocene. Thus it can be seen that once reduced to MSL the difference between the observed and predicted data is reduced significantly, with two of the observed points even falling on the predicted data curve (*c.* 4800 cal. BP and *c.* 2700 cal. yrs BP).

Once the correction for compaction had been added some of the observed data points were raised slightly but the data are still similar, especially when a sea-level band is added (Fig. 8.9). There appears to be a very close agreement between the observed and predicted data once the observed data has been corrected to MHWST and raised to allow for the effects of compaction. The only difference is that the gradient of the observed sea-level curve is slightly greater than the predicted data.

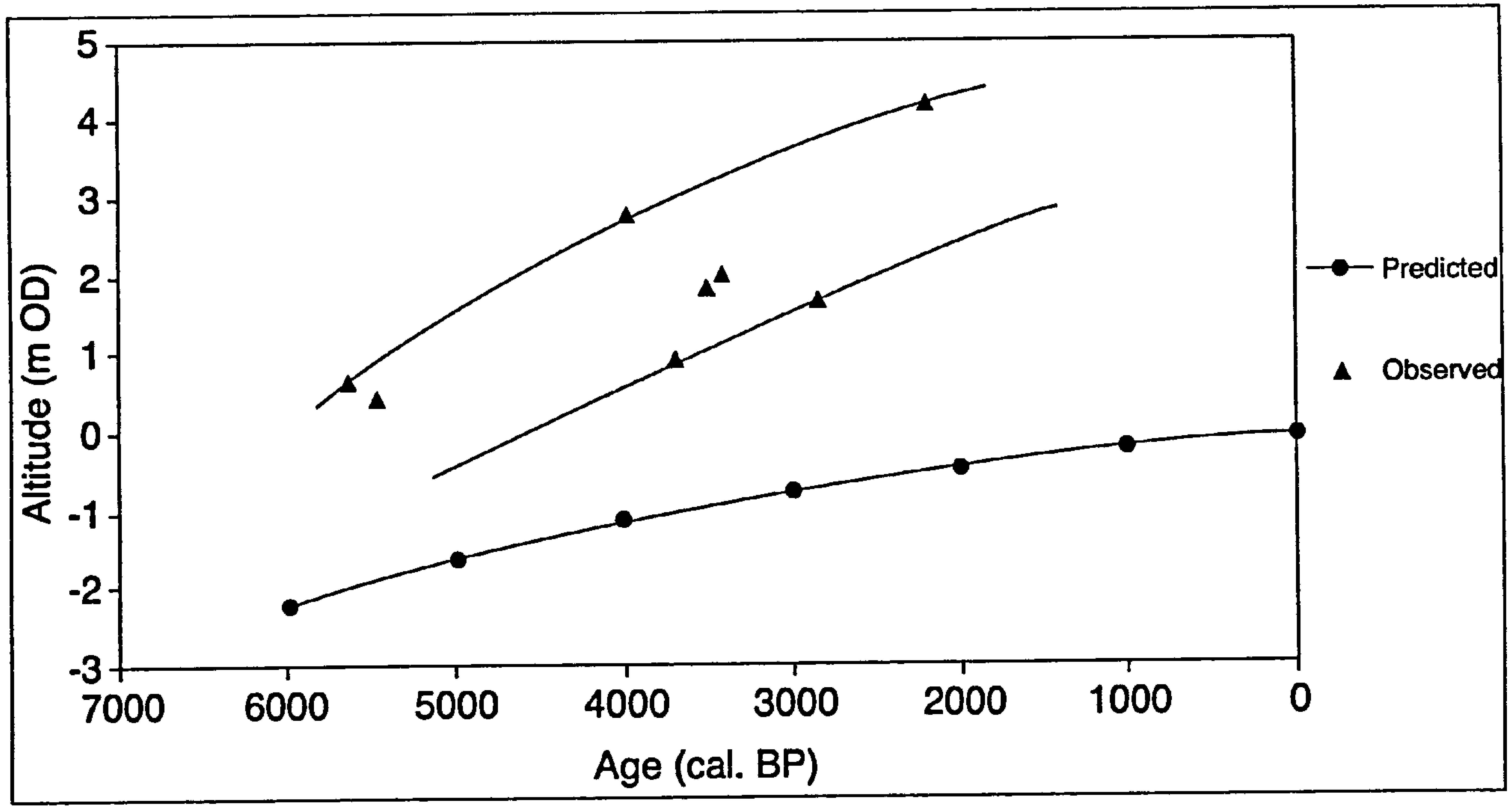


Fig. 8.4 Observed data (uncorrected) compared with predicted data for the Canche Estuary.

A sea-level band has been added to the observed data.

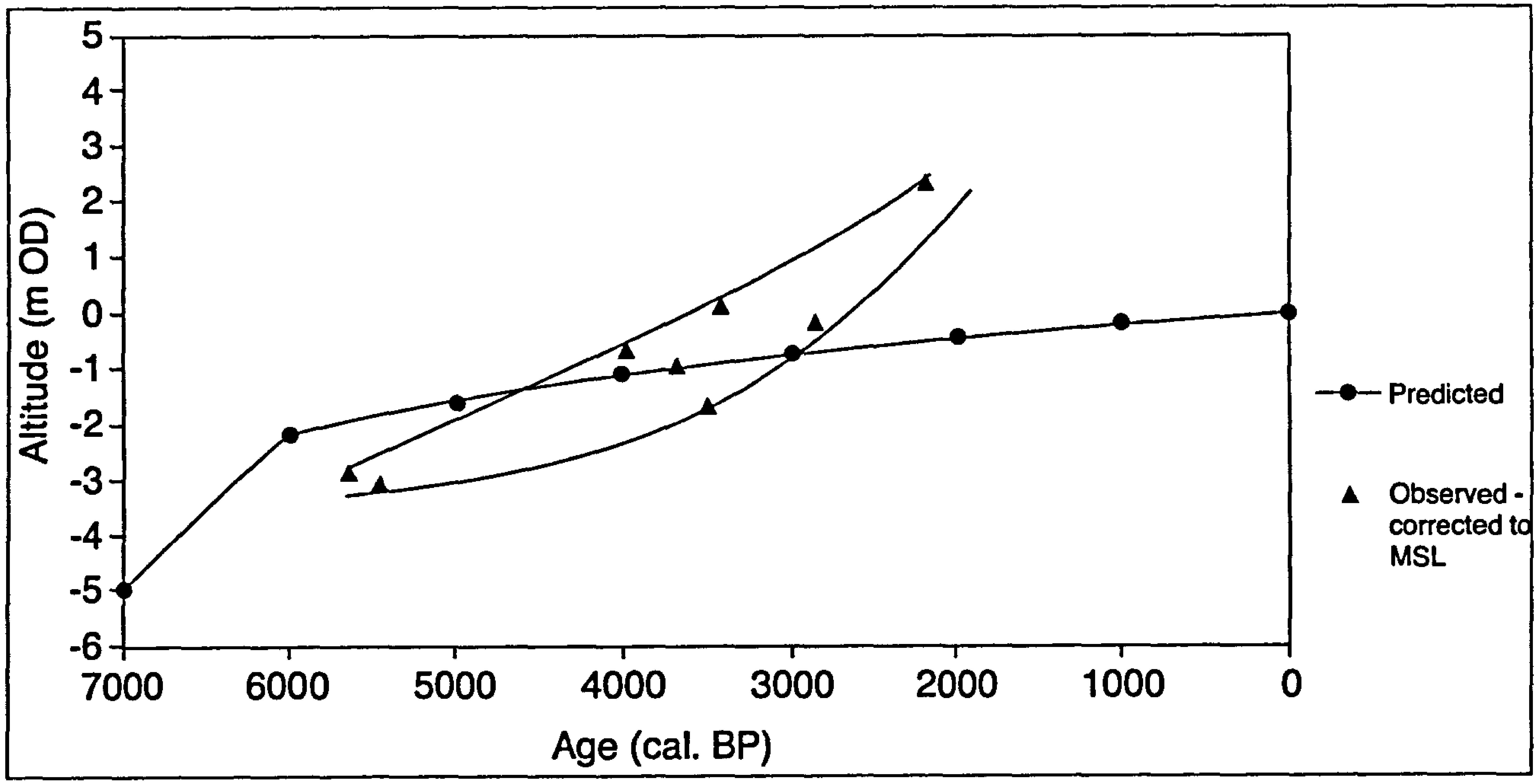


Fig. 8.5 Observed data corrected to mean sea-level (▲) compared with predicted data (•) for the Canche Estuary.

A sea-level band has been added to aid the comparison between observed and predicted data.

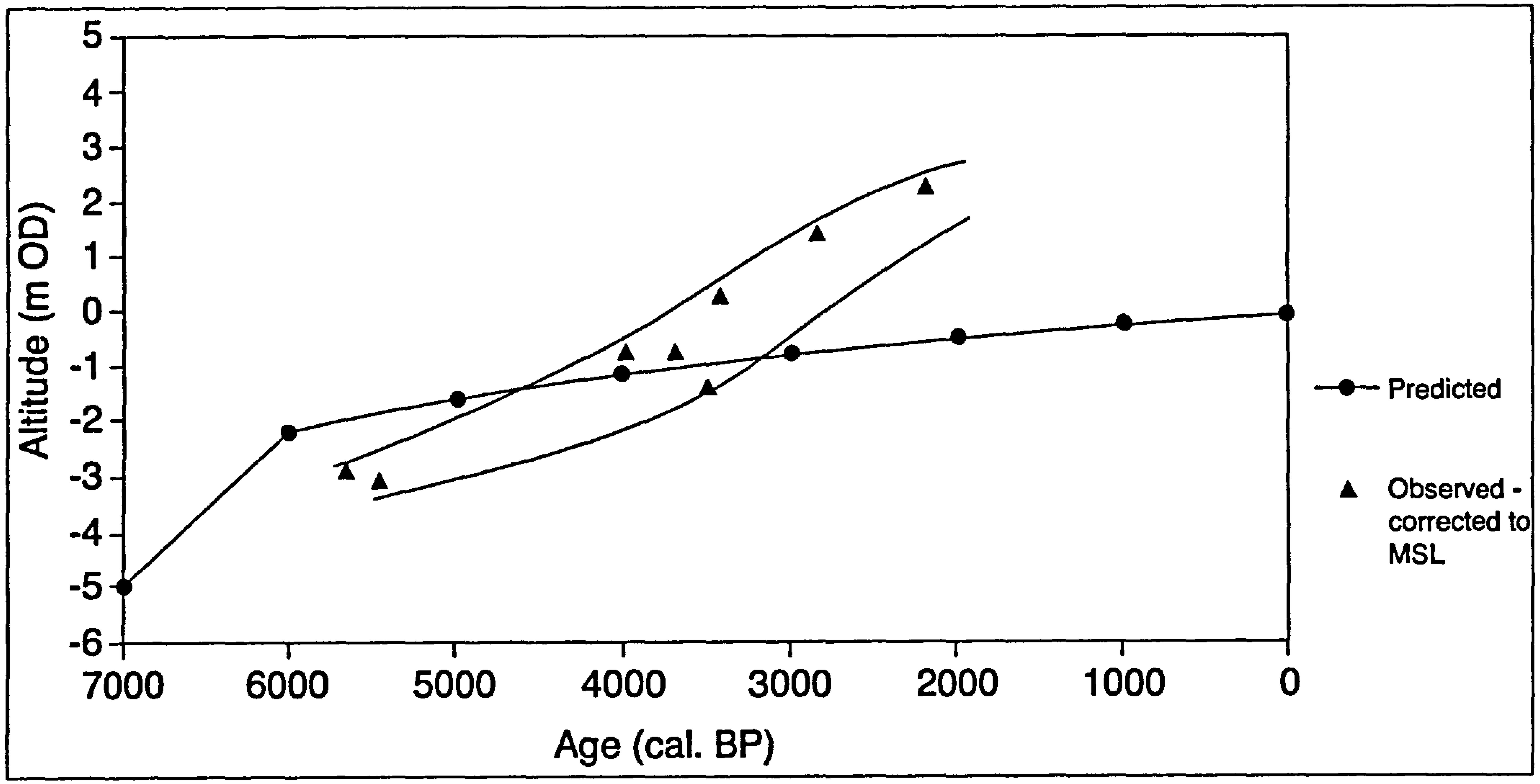


Fig. 8.6 Observed data (▲) corrected for an estimate of compaction and corrected to MSL plotted against predicted data (•) for the Canche Estuary. A sea-level band has been added to the observational data.

Type of deposit	Original altitude (m)	Radiocarbon Age (cal. yrs BP)	Correction required	Difference between correction and MTL	Corrected altitude (m)
Regressive	-1.11	6796	m^1 – 20cm 8.285 – 0.20 = 8.085	8.085 – 4.84 = 3.245	-1.11 – 3.245 = **-4.355**
Transgressive	-0.73	6827	MHWST – 20cm 6.92 – 0.20 = 6.72	6.72 – 4.84 = 1.88	-0.73 – 1.88 = **-2.61**
Regressive	-0.33	6821	m^1 – 20cm 8.285 – 0.20 = 8.085	8.085 – 4.84 = 3.245	-0.33 – 3.245 = **-3.575**
Transgressive	-0.10	6306	MHWST – 20cm 6.92 – 0.20 = 6.72	6.72 – 4.84 = 1.88	-0.10 – 1.88 = **-1.98**
Regressive	+1.06	5906	m^1 – 20cm 8.285 – 0.20 = 8.085	8.085 – 4.84 = 3.245	1.06 – 3.245 = **-2.185**
Transgressive	+2.42	2748	MHWST – 20cm 6.92 – 0.20 = 6.72	6.72 – 4.84 = 1.88	2.42 – 1.88 = **0.54**
Regressive	+2.80	2654	m^1 – 20cm 8.285 – 0.20 = 8.085	8.085 – 4.84 = 3.245	2.8 – 3.245 = **-0.445**
Transgressive	+3.15	1785	MHWST – 20cm 6.92 – 0.20 = 6.72	6.72 – 4.84 = 1.88	3.15 – 1.88 = **1.27**
Regressive	+3.39	1673	m^1 – 20cm 8.285 – 0.20 = 8.085	8.085 – 4.84 = 3.245	3.39 – 3.245 = **0.145**
Regressive	+0.07	5739	m^1 – 20cm 8.285 – 0.20 = 8.085	8.085 – 4.84 = 3.245	0.07 – 3.245 = **-3.175**
Transgressive	+0.37	4833	MHWST – 20cm 6.92 – 0.20 = 6.72	6.72 – 4.84 = 1.88	0.37 – 1.88 = **-1.51**
Regressive	+1.51	3757	m^1 – 20cm 8.285 – 0.20 = 8.085	8.085 – 4.84 = 3.245	1.51 – 3.245 = **-1.735**

Table 8.3 Corrections from MHWST to MSL for Estrébœuf, Somme Valley.

m^1 = (HAT+MHWST)/2 = 8.285. Tidal data provided by SHOM (2002)

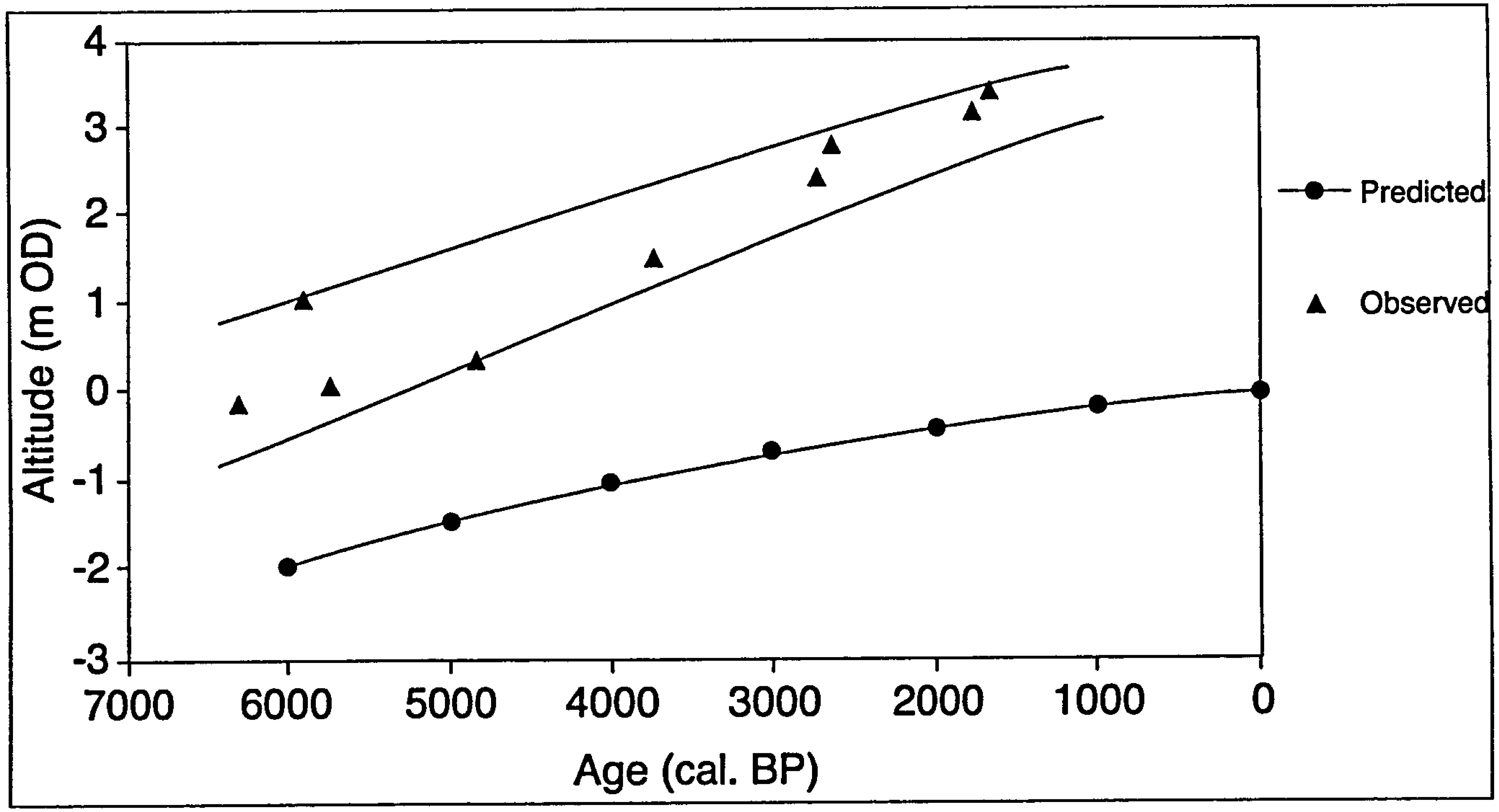


Fig. 8.7 Observed data compared with predicted data for the Somme Estuary.

A sea-level band has been added to aid comparison.

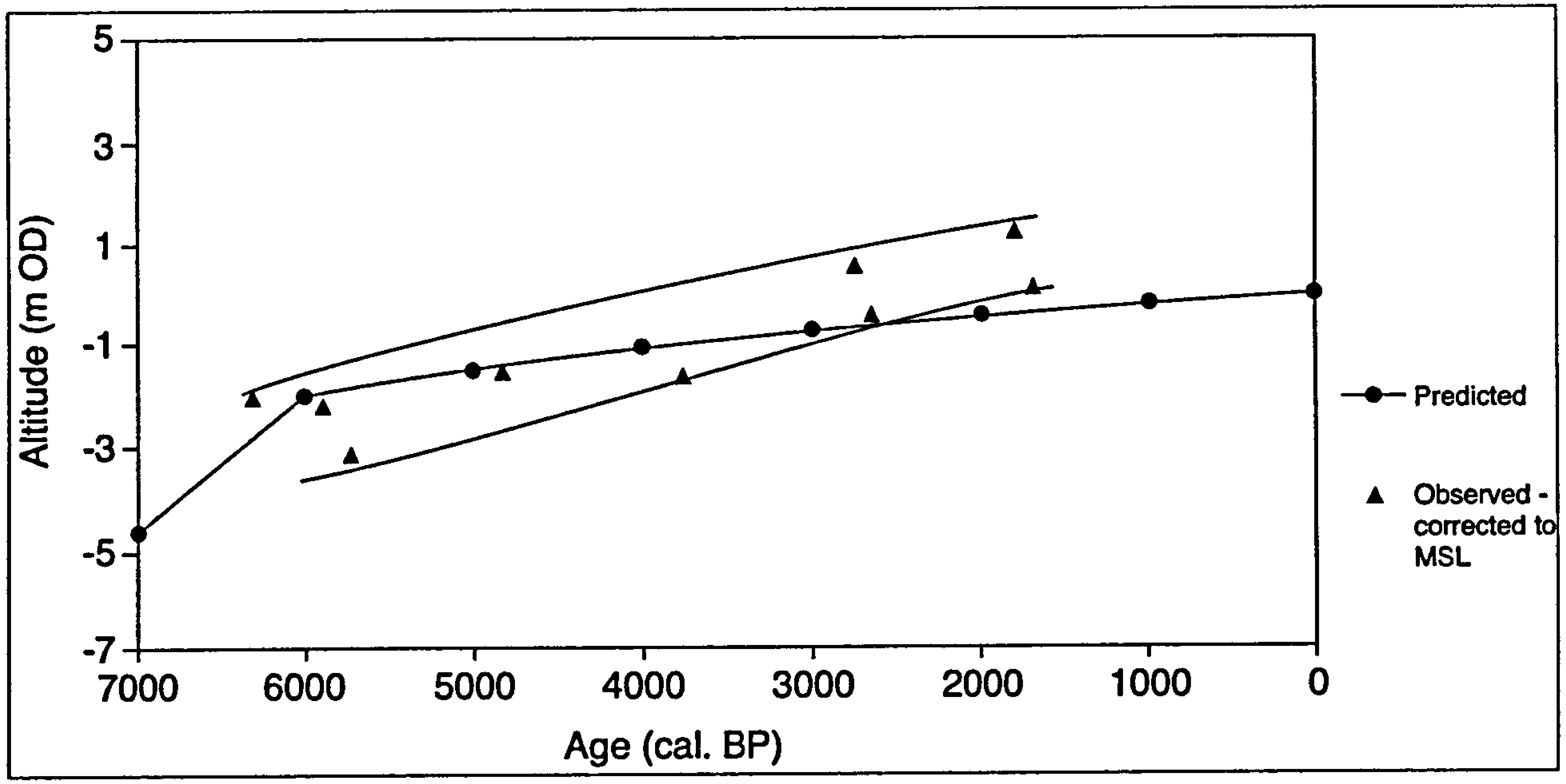


Fig. 8.8 Observed data corrected to mean sea-level compared with predicted data for the Somme Estuary.

A sea-level band has been added to assist in comparing the observed data to the predicted data

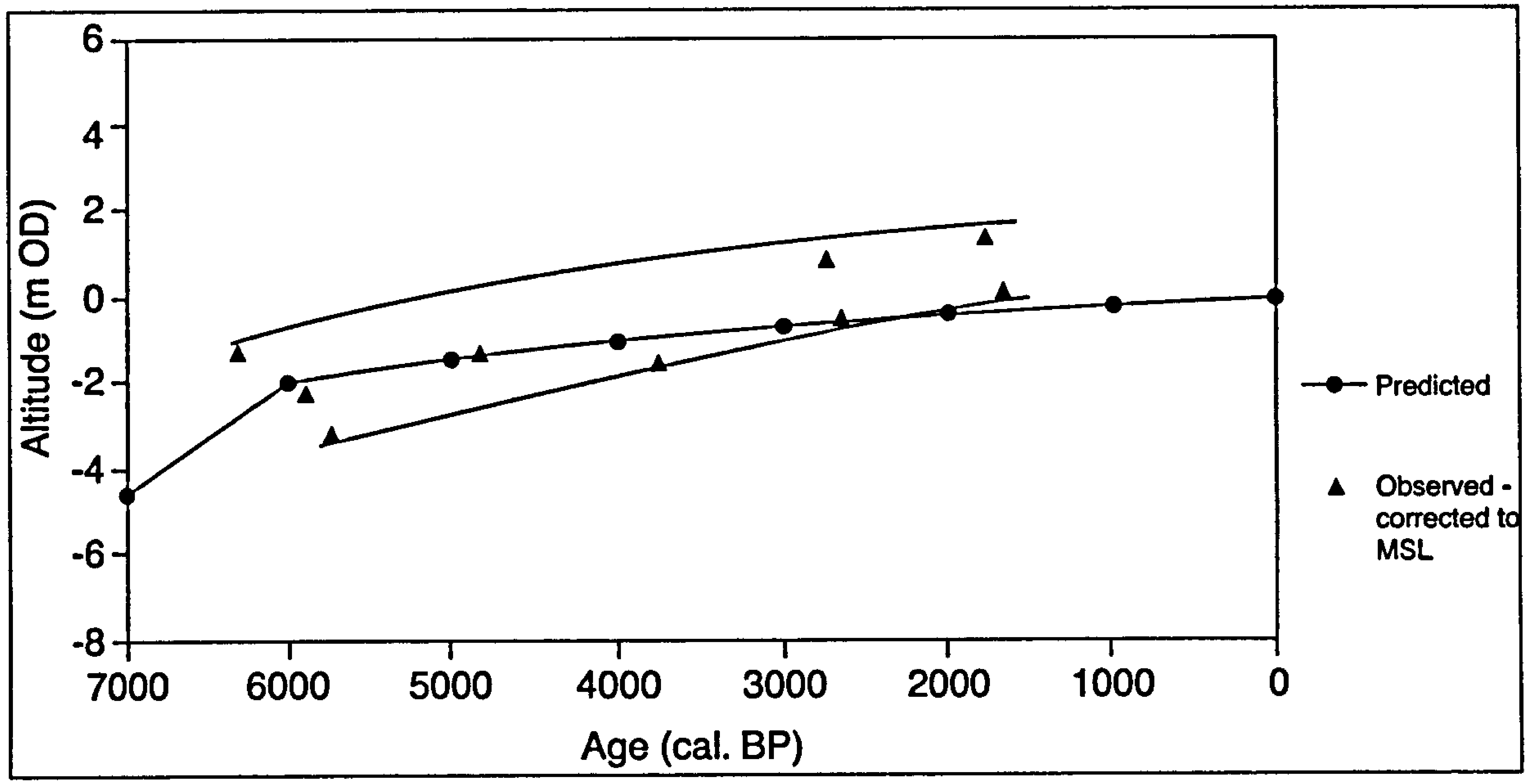


Fig. 8.9 Observed data corrected for compaction and relative to MSL (▲)

plotted against predicted data (●) for the Somme Estuary.

A sea-level band has been added to the observed data to aid in the comparison with the predicted data.

8.6 Discussion of the differences between observed and predicted data

A number of corrective terms need to be applied to the observational data in order for a direct comparison to be made with the modelled data. The modelled data are based on the reference water level MSL and the observational sea-level data represent deposition at or around MHWST, therefore, the observed index points needed to be lowered from MHWST to MTL. For transgressive overlaps the correction required at all the sites was MHWST-20cm and for the regressive overlaps was m^1-20cm (where m^1=(HAT+MHWS)/2) based upon the work of Shennan (1986b). However, this correction is performed using current tidal level information, as this is the only information readily available. Tidal range is known to have varied over time (Shennan *et al.* 2000a) and performing such a correction using current tidal data will therefore introduce an error. At first, this would suggest that the production of a reliable palaeo-tidal model would reduce the disparities between the data sets. In fact, research which developed a tidal model and corrected both the observed and modelled data to include these changes, actually found that the difference between the modelled and observed data increased (Shennan *et al.* 2000a). The palaeo-tidal model therefore requires further validation before it can be used to reliably correct sea-level data.

The differences that can be seen between the observed and modelled data sets from the Pevensey Levels could be the result of differences in the type of data obtained, as stated by Lambeck (1993) who commented that "the discrepancies noted for southern England may reflect the different nature of the observational data as much as the limitations of the model predictions" (p.984). It is therefore possible that the disparities between the observed and predicted data could be resolved by using recently obtained observations from sites in south east England to constrain the modelled data.

The results from the Canche and Somme estuaries in northern France showed a close agreement between the modelled and observed data, although there was a slight tendency for the observational sea-level index points to plot above the predicted sea-level curve. However, within the uncertainties that exist with any sea-level data, these differences were minor.

An alternative approach to constraining the data would be to assume that the modelled data produces a more accurate record of Holocene sea-level change than the observational record. It would then be possible to determine several of the correction terms using the model parameters. For example, an estimate of compaction could be performed where the observational data lie below the predicted data, as at the Pevensey Levels.

In order to provide an estimate of compaction, the model parameters for isostatic response and tidal data including MSL must be assumed to be correct. At Pevensey, where the model slightly over-estimates the altitude of relative sea-level, the difference between the observational data which has been corrected to MSL and the modelled data could be assumed to be the amount of sediment compaction. The result would be an increase in the altitude of the observational index points. Using the data points plotted on Fig. 8.2, the difference in metres between the height of the modelled data and the observational data ranges from 1m to 4m. In a core of 5m, which contains substantial intercalated peat deposits (see Chapter Two), it is possible that 20% compaction has taken place, suggesting that it could be possible to estimate compaction using the modelled data. Although this method would fail to account for differential compaction between sediment types within the core, it could produce a first-order estimate of compaction for an age-depth point along the data line, given a sufficient number of predicted and observed data points. It could also be used as a way of testing the accuracy and reliability of different compaction models.

8.8 Conclusion

It can be seen from the description and figures above that once the observational data has been adjusted to MTL and an estimate of compaction included, there is a good agreement between the observational data and the geophysical model for the Canche Estuary, Somme Estuary and the Pevensey Levels. At the Somme two of the observational data points were even found to lie on the predicted sea-level curve.

The comparison between the datasets has highlighted a number of methodological points which need to be considered before the datasets are examined. Data needs to be comparable and thus a number of corrective terms must be applied (Shennan, 1986b). Of these the most important term to emerge was the need for accurate and comparable tidal information to be used, in order to avoid encountering errors between the datasets.

For the sites in northern France, agreement must therefore be placed with Lambeck (1997) who stated that "within the uncertainties of the sea-level indicators the results for the past 8000 years are very comparable to the Picardie results" (p.18). The differences between the modelled and observed data are greater for south east England, however, the gradient of the observed sea-level curve is much steeper than that predicted by Lambeck (*pers. comm.)*, most likely caused by the influence of barrier dynamics upon the Pevensey coastline throughout the mid-Holocene.

The above discussion demonstrates that despite a number of discrepancies between the observed and predicted data, the new data obtained here could be used to improve Lambeck's (1997) geophysical model.

Chapter Nine Conclusion

9.1 Introduction

The aims of the research were to obtain new sea-level index points either side of the English Channel, in order to carry out a cross-channel comparison and test geophysical models of relative sea-level change. To achieve these aims three sites were examined; the Pevensey Levels, East Sussex, the Canche Estuary, Pas de Calais and the Somme Estuary, Picardie, the findings of which are summarised below. A comprehensive cross-channel comparison was undertaken, which revealed a number of similar transgressive phases throughout the mid- to late-Holocene period. However, as the research progressed it became apparent that the Pevensey Levels had been influenced by the presence of a coastal barrier, which affected the sea-level signals that were available from the site. It is also possible that a barrier existed at the Somme Estuary, although the sea-level signals obtained from this site do not appear to have been affected as much as they were on the Pevensey Levels or at the Canche. The effects of local and regional forces interacting were also seen to have an effect upon the relationship between the observed and modelled rates of sea-level change. The aim of this chapter is to provide a summary of the main findings and to discuss any future research.

9.2 Aims and objectives of the research

The aims of the project were as follows:

a) Examine any differences between the study areas either side of the English Channel and determine whether the controlling factors in the pattern of coastal evolution were local or regional.
b) Determine the extent of past changes in relative sea-level over the mid- to late-Holcoene and to provide an estimate of future sea-levels.
c) Compare observed data with the data provided by the geophysical models of past relative sea-levels (Lambeck, 1997, *pers. comm.*) in order to provide new data which could be used to validate the modelled data.

The aims and objectives have been successfully addressed other than that of predicting future trends. Distinct patterns of sea-level change have been identified and proposals have been presented which state whether the patterns are believed to be the result of local or regional factors. The results of a site-specific geophysical model have been compared to the observational data.

At this stage it is necessary to mention that as stated in the second research aim it was initially hoped that the examination and significance of past tends could be used to obtain future predictions sea-level change. However, this part of the research proved to be impractical because the most relevant part of the past record, namely the past 2000 years, is poorly represented at the sites that were investigated. Therefore, this research aim had to be excluded from the research.

9.3 Summary of findings at each study site

The Pevensey Levels, East Sussex

The coastal sedimentation at the Pevensey Levels, East Sussex revealed a complex stratigraphic record indicative of a series of relative sea-level movements coupled with changes in the dynamics of the mid-Holocene coastal barrier that was present. Six stratigraphic units were identified, which included two peat layers, intercalated between silt and clay units. The AMS radiocarbon dates produced two clusters of sea-level index points when plotted on the age-altitude graph (refer to Fig. 4.8 in Chapter Four). These results suggested that a three-phase model of coastal development could be seen at Pevensey over the mid- to late-Holocene.

The diatom and foraminiferal data showed that sediments deposited prior to 4500 cal. years BP (Phase one) were laid down under marine conditions, most likely tidal flats. Phase two was marked by the onset of peat development across the Levels, at around 4000 cal. years BP. The pollen from this lower peat revealed that it formed initially under decreasingly marine conditions, followed by a transition to salt marsh taxa, believed at other sites to be indicative of a slowly rising sea-level and the presence of a coastal barrier (Long & Innes, 1993). During this phase, the barrier would have extended across the coastline, protecting the estuary from being permanently flooded. The thin silty unit that was recorded within the peat layer in the sample core (PL BH2) represented a tidal channel, shown by the presence of the salt marsh foraminifera *Jadammina macrescens* and the tidal flat diatom species *Acnanthes delicatula*. The presence of inorganic layers, similar to these, has also been noted at Romney Marsh and on the Willingdon Levels, (Long & Innes, 1993 and Jennings & Smyth, 1982) which were attributed to migration of river channels or periodic barrier breaching. Since most sites never become fully isolated from the sea, a current working hypothesis suggests that these small lenses of inorganic deposits are not indicative of a relative change in sea-level but simply indicate a change in barrier dynamics. The final phase at Pevensey was marked by the breakdown of the coastal barrier *c.* 2000 cal. years BP, concurrent with a rise in relative sea-level.

The Canche Estuary, Pas de Calais

The stratigraphic survey undertaken at the Canche identified ten sediment units, including two buried peat layers and two silty peat transitional units. The onset of the lower peat marked the first regressive episode, 5500 cal. years BP with the biostratigraphy showing the presence of salt marsh indicators. The first transgressive overlap was obtained from the shift to the upper silty peat, dated to around 3700 cal. years BP. The onset of the second organic layer marked the second regressive event *c.*3500 cal. years BP, followed shortly by the second transgressive episode *c.* 3430 cal. years BP. A final transgressive event, dated to around 2200 cal. years BP, was recorded in core CA BH10 but not in the sample core CA BH9. Although a similar late-Holocene transgressive event has been recorded at other sites either side of the Channel. In addition to this there was no evidence to support the theory that sea-level rose above the present-day level as had previously been thought (Agache *et al.*, 1963).

The Somme Estuary, Picardie

The stratigraphy recorded at the Somme represented the greatest number of stratigraphic units encountered at the study sites. In the sample core, eleven units were identified, including four buried peat layers. AMS radiocarbon dating results were inconclusive and therefore there were inconsistencies in the timings of the relative sea-level movements from the lowest three units, despite the fact that the biostratigraphic data indicated changes in the pattern of coastal deposition. Therefore, sea-level index points could not be obtained from these units. The first transgressive event appeared to have taken place at around 6300 cal. years BP, at the boundary between the lower woody peat and a sand layer. However, insufficient palaeoecological data were obtained to assign an indicative meaning. The first reliable sea-level index point was obtained from a regressive overlap dated 5900 cal. years BP. Sea-level remained low until 2750 cal. years BP, when a shift to sandy peat was shown by the diatoms and foraminifera to represent an inter-tidal deposit. However, by 2650 cal. years BP, sea-level had fallen once again. The final transgressive overlap was recorded slightly later than at Pevensey or the Canche, at around 1785 cal. years BP, marked by the end of herbaceous peat development.

The presence of a coastal barrier between 5000 and 3000 cal. years BP (Buen & Broquet, 1983) could explain the lack of sea-level index points obtained between 5900 cal. years BP and 2750 cal. years BP. Throughout this period, the estuary would have been largely protected from any marine influence, allowing an extensive salt marsh to develop, which would have only been flooded at high tide, explaining the occurrence of some marine diatoms and foraminifera. The new sea-level index points reveal that barrier breakdown most likely resulted from a rise in relative sea-level, coupled with changing barrier dynamics and was not the result of human activity as previously believed (Buen & Broquet, 1983). The research has highlighted the importance of using biostratigraphic data to validate transgressive and regressive overlaps and demonstrated the need for a diatom-based transfer function calibrated in northern France.

9.4 Cross-channel comparison

Despite the apparent site-specific controls which have been identified as the dominant control on the sea-level signal, there appears to be a clear correlation between the timing of transgressive sea-level movements either side of the English Channel. Widespread change has been recorded around 5500 years BP, 3200-3000 years BP and 2000-2200 years BP. The results from Pevensey revealed that a cross-channel transgressive episode similar to that which took place in Essex, Romney Marsh and at the Canche Estuary (refer to Table 7.2.3.1 in Chapter Seven) *c.* 2700-2800 cal. years BP had taken place.

The results from the cross-channel comparison compared well to previously published data from sites in both south east England and northern France, with similar timings of barrier development and relative sea-level rise being seen at Romney Marsh, Kent and at the Somme Estuary, Picardie. Most notable is the slowing rate of sea-level rise seen throughout the mid-Holocene, a phenomenon previously recorded by many authors (Long & Innes, 1993, 1995; Spencer *et al.* 1998, Jennings & Smyth, 1987, 1988 and Ters, 1986). At around 2200 cal. years BP, a second channel-wide transgressive event can be seen to take place at Pevensey, Romney Marsh, Eastbourne, sites along the Atlantic Coast and at the Canche Estuary (refer to Table 7.2.3.1 in Chapter Seven).

The age-depth plot from the Canche showed a curvilinear rising sea-level throughout the mid-to late-Holocene. The final transgressive event, *c.* 2200 cal. years BP, is of particular importance because a similar transgressive event was recorded at Romney Marsh, the Pevensey Levels and at sites along the Atlantic coast. There is no evidence for the presence of a mid-Holocene coastal barrier at the Canche Estuary, strengthening the proposal that this late-Holocene event represents a channel-wide rise in relative sea-level.

The timing of the marine transgressive phases recorded at the Somme compared well with those from the Pevensey Levels and Romney Marsh, both of which show evidence for the existence of a coastal barrier throughout the mid- to late-Holocene. The mid-Holocene transgression *c.* 5300 years BP was also recorded at Romney and Lagney Point (Jennings, 1985). However, the final transgressive overlap at the Somme was recorded around 1800 years BP. This was the youngest transgression recorded by this research.

It can be seen from the above discussion that although the cross-channel temporal comparison revealed a number of similar transgressive events indicating a possible channel-wide signal of late-Holocene sea-level change, local coastal processes appear to have remained dominant throughout the mid- to late-Holocene. Thus the usefulness of performing such a comparison has been highlighted. Examination of the regional trends can allow these local signals to be detected, without such a comparison it would be difficult to determine whether changes in relative sea-level had resulted from changes in the local coastal dynamics or more regional controls.

9.5 Comparison between observed and predicted data

The general trends and patterns of predicted sea-level change were seen to compare well with the observed data. However, as has been shown in previous research (Shennan *et al.* 2000a) the model slightly over-estimated the altitude of relative sea-level rise in south-east England, but slightly under-predicted the altitude at the French sites. This variation can be explained by the inherent problems that are experienced by using geophysical models to determine relative sea-level.

The comparison between the modelled and observed data from the Pevensey Levels revealed a number of inconsistencies. The modelled data predicted a smoothly rising curve of relative sea-level. The observed data presented with a sea-level "envelope" also revealed a fairly smooth rising sea-level, but the two distinct clusters of index points could still be seen. This could imply that using modelled data to determine past sea-levels produces a more accurate pattern of sea-level change because the sea-level signal is not affected by local coastal processes. At present localised parameters, such as sediment compaction, tidal range and sedimentation rates, are not included in the geophysical models and although a similar general pattern of relative sea-level rise can be observed when the data are monitored over a substantial period of time, if these local parameters were incorporated into the model it could perhaps produce results closer to that produced using the observational data.

The comparison between the modelled data and the observed data from the Canche Estuary showed a good agreement over the last 6,000 years. At the Somme, the observed pattern of relative sea-level rise also matched the predicted pattern very closely, in particular over the last 6,000 years, with some observed data points plotting on the predicted sea-level curve. Initially the model under-predicted the altitude of the sea-level change, however if local factors, such as compaction correction and variations in tidal range are to be accounted for, it could again become apparent that the modelled data is more accurate than the observed data.

9.6 Intrinsic methodological shortcomings

The study demonstrated that the methodological techniques involved in the studies greatly affect the ability to perform a cross-channel comparison. Previous attempts to carry out such comparative research were hindered by the type of data that was available. Thus, the collection of new sea-level data with the specific intention of performing a cross-channel study was required. Many of the errors involved in collecting and evaluating observed sea-level data were thoroughly discussed by Heyworth & Kidson (1982) and are therefore not presented here.

The results of the biostratigraphic analyses revealed variable results. Pollen analysis proved useful in trying to determine whether a peat sample represented deposition under a salt marsh environment or was deposited above any marine influence, i.e. below or above MHWST, providing initial information about possible changes in sea-level. The results obtained from the diatom analysis allowed information about past tidal levels to be obtained from the inorganic stratigraphic units, where pollen analysis had failed to determine the depositional origin, except where dissolution had occurred. Unfortunately, the results of the foraminiferal analysis were discouraging. Many sedimentary units contained either too few or no preserved foraminiferal tests, thus adding little more information than had already been presented by the pollen and diatom data. In particular the findings from the lower sandy sediments at the Canche and Somme were disappointing. Low foraminiferal counts are a commonly encountered problem in fossil sequences, with typical counts reaching only 100 tests (Haslett, 1997; Gehrels *et al.*, 2001). However, many of the samples studied in this research failed even to reach the minimum acceptable level of 30 (Gehrels *et al.* 2001). The implication of these low counts was that the results could not be validated using a foraminiferal-based transfer function.

It is also possible that the sampling strategy that was used in this research resulted in a number of interpretational problems. Palaeoecological sampling was concentrated across stratigraphic boundary changes, however in order to aid the comparison between sites this data was then constrained according to the stratigraphic units. This has the limitation of implying that most changes took place between the sediment units, not within the sediment units. Thus, when such an approach is employed careful attention must be paid to within unit changes in order not to overlook changes in relative sea-level.

The calibration of the diatom data from France with the diatom-based transfer function (Zong & Horton, 1998, 1999) also provided disappointing results. The transfer function failed to accurately determine past tidal levels for many of the dated transgressive and regressive overlaps, making assigning a precise indicative meaning difficult. This problem is believed to be the result of the species that were identified at these sites. Many of the species, in particular the freshwater species, were not present in the training set. The most likely reason for this is that the transfer function was developed using modern day assemblages from north-eastern England, which exhibited different diatom taxa to sites in northern France. The sediments found in north eastern England also differ considerably to those recorded in northern France, in particular a greater sand fraction is found in the lower units of the French sediments. The development of a more complete diatom-based transfer function from the present-day salt marsh at the Somme Estuary would resolve this issue if a suitable upper marsh environment can be sampled and add to the limited number of transfer functions in existence.

An alternative approach to test the data could employ a foraminiferal-based transfer function (Horton, 1999). This would overcome many of the problems since these transfer functions have been developed to include sandier deposits. If the transfer functions also encountered similar problems in the species encountered then it could make better sense to adopt an indicator-species approach. However, this approach relies heavily upon the presence of sufficient tests, and on the species encountered, and could make drawing comparisons between sites more difficult if the same indicator-species are not recorded.

During the construction of the age-depth plots for each site and the reconstruction of many of the previously published sea-level curves, several inherent problems were encountered. Much of the existing data had assumed that the dated transgressive and regressive overlaps were deposited at or around the height of mean high water spring tide. However, few of these studies had employed transfer-functions to determine the accurate palaeo-tidal level. The biostratigraphic results clearly showed that not all the peat deposits had developed at mean high water spring tide. Therefore, the sea-level index points need to be corrected by the difference between the palaeo-tidal level determined by the transfer function and the height of mean high water spring tide. It is therefore particularly important when attempting to draw comparisons between sites to know what the reference water level is; mean high water spring tide or mean sea-level. For many of the sites in France it appeared that no such correction had taken place. However, without detailed information about the biostratigraphy of the dated points, this correction could not be reliably performed. Therefore, many of the previously published age-depth plots presented in this research had to be presented relative to the datum height (NGF), in order to allow for comparisons.

The issue of sediment compaction must also not be overlooked. Although this study did provide an estimate of sediment compaction for each of the study sites, it was only an estimate. Although several methods do now exist (Haslett *et al.* 1997; Paul & Barras, 1998 and Allen, 1999, 2000), to date no single reliable method has been developed for research on palaeo-coastal sites. There is a clear need for the development of a reliable calculation of sediment compaction for sediments including clay, silt, sand and peat, and mixtures of these components.

Although some of these inherent methodological errors were dealt with by this research, many of them proved beyond its scope. The need for further research can therefore be identified, including research at the field sites and improvements in the methodologies employed.

9.7 Future research

At each of the study sites the need to obtain early-Holocene deposits became evident. The collection of basal or lower peat layers, thought to be present at each of the sites (BGS and BRGM data), could provide essential information about the degree of compaction and consolidation of the sediments. These lower or basal peats rest on a incompressible sediment layer which will not have been subjected to any sediment compaction. This allows a reference depth to be obtained, against which subsequent stratigraphic contacts can be compared. Without these data it was impossible to accurately determine the amount of compaction that had taken place.

Secondly, verification of some of the AMS radiocarbon dates obtained is necessary. In particular, the lowest three dates obtained from the Somme need to be checked in order to determine whether the lower sediment units recorded in the sample core can yield sea-level index points.

In addition to the biostratigraphic data that was collected from the sample cores, the need for additional analytical techniques was highlighted. Particle size analysis and mineral magnetic analysis of the sediments could help determine the source sand units, where the biostratigraphic data failed to produce conclusive results. Secondly, and possibly more importantly further research is required on the upper units recovered at the sites in an attempt to determine the pattern of change over the last 2000 years and see if an increase in storm activity can be identified (Plater *et al.*, 1999).

Where the diatom-based transfer function failed to accurately predict palaeo-tidal levels, due to discrepancies with the species data, it may prove useful to use an alternative micro-fossil based transfer function. Horton *et al.* (2000) suggest a number of transfer functions that can be applied. For this particular study if a sufficient number of foraminiferal tests can be recovered from the sediments, the use of a foraminiferal-based transfer function may aid in elucidating the pattern of relative sea-level change, where the diatom data proved inconclusive.

Finally, the development of a diatom-based transfer function using modern day analogues collected from the salt marsh and sand flats at the Somme is required. Not only would this add to the transfer function data that is currently available, it would form the first such study to be undertaken in France.

9.8 Conclusion

"Holocene sea-level changes in south east England and northern France" has provided the first comprehensive directly comparable cross-channel comparison of mid- to late-Holocene sea-level changes. A number of important transgressive phases have been identified either side of the English Channel, *c.* 5000 years BP; 2700-2800 years BP and 2000 years BP, which at Pevensey and the Somme appear to represent barrier initialisation and breakdown. The multi-proxy approach was mostly successful and highlighted the importance of obtaining accurate biostratigraphic data in order to determine past tidal levels.

Despite the findings that local controls had dominated the pattern of relative sea-level change and coastal sedimentation at the study sites, the performance of a cross-channel comparison can still be justified. Without the cross-channel comparison it would have been difficult to decipher whether the signals were regional or local, thus leaving many of the research questions unanswered. In addition to this, it may be possible in the future to use the regional signals to produce estimates of crustal movement, changes in tidal range and localised sediment compaction and consolidation (Shennan, 1987).

Comparisons between the observed and geophysically modelled data found the pattern agreed closely, in particular at the French sites, but that at all sites the model still slightly under-predicted the altitude of sea-level rise. The research has provided new data, which can be used to assist in the validation of the geophysical models.

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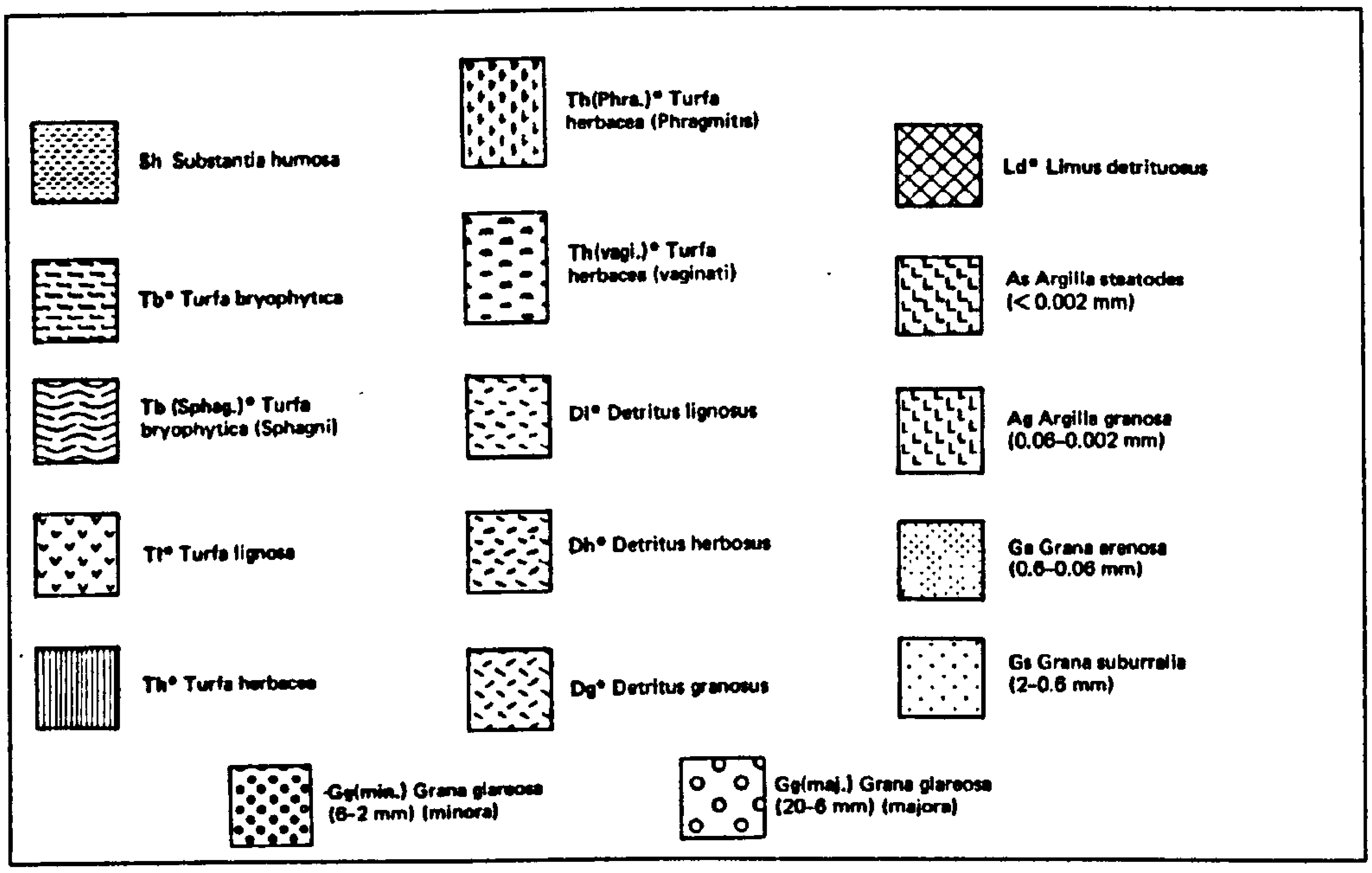
Appendix I
Troels-Smith Classification



Class	Symbol	Sediment	Description
Turfa	Tb$^{0-4}$	T. bryophytica	Mosses, +/- humous
	Tl$^{0-4}$	T. lignosa	Stumps, roots, branches of ligneous plants
	Th$^{0-4}$	T. herbacea	Roots, rootlets, rhizomes of herbaceous plants
Detritus	Dl	D. lignosus	Fragments of ligneous plants
	Dh	D. herbaceous	Fragments of herbaceous plants
	Dg	D. granosus	Fragments of ligneous and herbaceous plants, with animal fossils
Limus	Ld$^{0-4}$	L. detrituosus	Plants and animal fragments, humous
	Lso	L. siliceus	Diatoms, siliceous remains
	Lc	L. calcareous	Marl
	Lf	L. ferrugineus	Iron oxide
Argilla	As	Clay	Particles <0.002 mm
	Ag	Silt	Particles 0.002 – 0.06 mm
Grana	Ga	Fine sand	Particles 0.06 – 0.6 mm
	Gs	Coarse sand	Particles 0.6 – 2 mm
	Gg	Gravel	Particles > 2 mm
Substantia humosa	Sh	Humous substance	Disintegrated organic substances and precipitated humic acids

Adapted from Birks & Birks (1980)

Appendix II

Stratigraphic Survey Results

Stratigraphic descriptions for Pevensey Levels, East Sussex

Coastal core

Depth (m)	Depth OD	Description and Components	Nig	Strf	Sicc	Elas	Lim supp
0-18	0-18	Rooty peat	0	0	0	0	0
18-66	18-66	Grey silty sandy clay Ga1 As1 Ag2 *Part. test* +	2	0	2	0	1
66-105	66-105	Coarse dark grey sand silt and clay Gs2 As1 Ag1	3	0	2	0	1
105-112	105-112	Medium gravel As3 Ag1 Ga + Gg (maj) +	2	0	3	0	1
112-120	112-120	Black sandy clay and silt As3 Ga1	4	0	2	1	1
120-136	120-136	Grey sandy clay As3 Ga1	2	0	1	1	1
136-145	136-145	Yellow brown sand and clay As2 Ga2	2	1	2	1	

PL-5

Depth (m)	Depth OD	Description and Components	Nig	Strf	Sicc	Elas	Lim supp
0-6	1.454-1.394	Topsoil	0	0	0	0	0
6-72	1.394-0.734	Brown grey silty clay As2 Ag2	2	0	1	3	2
72-176	0.734 – - 0.306	Bands of sand within silty clay As2 Ag1 Ga +	2	1	1	3	2
176-196	- 0.306 - - 0.506	Grey silty sandy clay As2 Ag1 Ga1	2 +	3	3	0	3
196-266	- 0.506 - - 1.206	Clay As4 Ag +	3	3	3	0	2
266-279	- 1.206 - - 1.336	Woody peat – erosive layer Tl4	0	0	0	0	2
279-465	- 1.336 - - 3.196	Black organic streaks within clay As4 Ag + Ga +	3+	4	3	3	2
465 – 679	- 3.196 - - 5.336	Very dark grey silty clay As3 Ag1	4	1	3	3	2

PL-4

Depth (m)	Depth OD	Description and Components	Nig	Strf	Sicc	Elas	Lim supp
0-9	1.519-1.429	Topsoil	0	0	0	0	0
9-35	1.429-1.169	Silty clay As2 Ag2	2	1	1	1	1
35-87	1.169-0.649	Brown grey very dry and hard As2 Ag2 Ga +	2	0	1	1	2
87-98	0.649-0.536	As2 Ag2	2	0	1	1	2
98-164	0.536 - -0.121	Dry hard silty clay with pockets of sand and calcareous nodules As2 Ag2 Ga +	2+	0	3	1	1
164-190	-0.381 - -0.801	Grey clay with some silt As4 As +	3	0	1	1	1
190-232	-0.801 - - 1.341	Organic staining As3 Ag1	3	0	1	1	2
232-286	- 1.341 - - 1.591	Eroded peat within silty clay As3 Ag1 Tl +	2	1	2	1	3
286-311	- 1.591 - - 1.951	Woody peat Tl4	3	0	0	0	3
311-347	- 1.951 - - 2.041	Silty clay As3 Ag1	2+	0	2	2	1
347-352	- 2.041- - 2.091	Tl4 – eroded peat	3	0	0	0	0
352-414	-2.091 - - 2.621	Dark grey silty clayAs3 Ag1	3	1	2	2	3

PL-3

0-8	1.366 – 1.286	Topsoil					
8-127	1.286 – 0.096	Oxidised hard silty grey clay As2 Ag2	2	0	3	2	1
127-178	0.096 - -0.414	Woody peat Tl4	3	0	2	2	2
178-183	-0.414 - -0.464	Very dark woody peat Tl4	4	0	2	2	4
183-192	-0.464 - -0.554	Woody peat Tl4	3	0	2	3	2
192-196	-0.554 - -0.594	Large piece of wood	3	0	2	3	3
196-218	-0.594 - -0.814	Woody peat Tl4	3	0	2	3	3
218-224	-0.814 - -0.874	Silty clay As3 Ag1	2	0	1	1	3
224-390	-0.874 - -2.534	Sand bands within silty clay As2 Ag1 Ga1	2+	2	2	1	3
390-422	-2.534 - -2.854	Dark grey sandy silty clay As2 Ag1 Ga1	3	2	2	1	1
422-466	-2.854 - -3.294	Dark sandy silty clay As2 Ag1 Ga1	3	0	2	1	1

PL –2

0-10	1.219 – 1.119	Topsoil	0	0	0	0	
10-160	1.119 - -0.381	Silty clay with calcareous nodules As3 Ag1	2	0	2	2	1
160-190	-0.381 - -0.631	As3 Ag1 black organic flex	2	0	2	2	1
190-280	-0.631 - -1.581	Red brown woody peat Tl4	3	0	0	0	1
280-387	-1.581 - -2.651	As3 Ag1 Grey clay	2	0	2	2	2
387-785	-2.651 - -6.631	Silty clay with organic flex As3 Ag1 Th +	2	0	2	2	4

PL –1

0-12	1.143 – 1.023	Topsoil	0	0	0	0	0
12-137	1.023 - -0.227	Silty clay oxidised As3 Ag1	2	0	2	2	1
137-188	-0.227 - -0.737	Grey silty clay with organic flex As3 Ag1 Th +	2+	0	3	3	1
188-190	-0.737 - -0.757	Erosional boundary dark brown peat	3	0	2	2	1
190-214	-0.757 - -0.997	Woody peat well decomposed Tl4	3+	0	0	0	0
214-220	-0.997 - -1.057	Clay As4 Ag +	2	0	3	3	0
220-235	-1.057 - -1.207	Woody peat Tl4	2+	0	0	0	0
235-238	-1.207 - -1.237	Organic clay As3 Sh1 +	2+	0	0	0	1
238-290	-1.237 - -1.757	Blue grey clay with organic flex As4	2+	0	2+	2	4
290-690	-1.757 - -5.757	Grey sand (Possibly a peat layer at 313-323cm depth)	2+	1	2	2	0

PL 3

0-30	1.414 – 1.114	Topsoil	0	0	0	0	0
30-106	1.114 – 0.354	Silty clay oxidised As2 Ag2	2	0	2	1	0
106-200	0.354 - - 0.586	Sandy silty clay Ga2 Ag1 As1	2	1+	3	1	0
200-216	- 0.586 - - 0.746	Sandy with some silt and clay Gs3 Ag1 As +	3	1+	0	0	0
216-233	- 0.746 - - 0.916	Ga2 Ag1 As1	2	1	3	1	0
233-251	- 0.916 - - 1.096	As3 Ag1 Ga +	2+	2	2	4	1
251-257	- 1.096 - - 1.156	Dark grey clay and sand Ga1 Gs1 As2	3	0	3	1	1

PL 4

0-18	1.484 – 1.304	Topsoil	0	0	0	0	0
18-182	1.304 - - 0.336	Oxidised silty clay As2 Ag2	2	0	2	1	0
182-193	- 0.336 - - 0.446	Silty clay As2 Ag2	2	0	2	1	0
193-198	- 0.446 - - 0.496	Woody peat – erosive contact Tl4	3	0	0	0	0
198-235	- 0.496 - - 0.866	Compacted peat Th (Phra) 4	3	0	0	0	3
235-400	- 0.866 - - 2.516	Sandy clay As3 Ga1	2	1	3	0	2

PL 1

0-14	1.484 - 1.344	Topsoil	0	0	0	0	0
14-143	1.344 – 0.054	Grey oxidised silty clay Ag2 As2 Th1+	2	0	2	1	0
143 – 149	0.054 - - 0.01	Clay with peat bands As4 Th +	3	0	0	0	1
149 – 167	- 0.01 - - 0.186	Woody peat Tl4	0	0	0	0	0
167 – 170	- 0.186 - - 0.216	Woody peat Tl4	0	0	0	0	0
170 – 194	- 0.216 - - 0.456	Peat with clay Tl3 As1	2+	0	2	3	2
194 – 211	- - 0.456 - - 0.626	Well humified peat Th4	0	0	0	0	0
211 – 338	- 0.626 - - 1.896	Organic silty clay with bands of sand As3 Ag1 Th1+ Ga +	1+	0	1	2+	3
338 – 449	- 1.896 - - 3.006	Grey silt sand and clay As1 Ag1 Ga2	2	2	2+	2	1

PL 2

0-21	1.213 – 1.003	Topsoil	0	0	0	0	0
21-156	1.003 - - 0.347	Silty clay organic flex and calcareous nodules As2 Ag2 Th1 +	1	0	3	0	0
156-162	- 0.347 - - 0.407	Grey brown silty clay As3 Ag1	1+	0	3	3	1
162-169	- 0.407 - - 0.477	Well humified black peat Th4	3+	0	4	0	1
169-192	- 0.477 - - 0.707	Woody peat Tl4	3	0	2+	3	2
192-195	- 0.707 - - 0.737	Organic clay As3 Th (Phra) 1	2	0	2+	3	2
195-240	- 0.737 - - 1.187	Dark brown peat Th (Phra) 1 Tl 3	3	0	0	0	2

240-377	- 1.187 - - 2.557	Soft blue clay organic flex As3 Ag1	2	0	3	3+	3+
377-431	- 2.557 - - 3.097	Sand Ga3 Ag1	2	0	3	2	1
PL 5							
0 – 17	1.087 – 0.917	Topsoil	0	0	0	0	0
17 – 139	0.917 - -0.303	Oxidised grey clay with calcareous nodules As2 Ag2	2	0	2	1	0
139 – 141	-0.303 - - 0.323	Dark clay As2 Ag2	4	0	2	1	1
141 – 174	- 0.323 - - 0.653	Dark brown Phragmites peat Th(Phra)4 Th¹ near lower contact	3	0	2	1	3+
174 – 180	- 0.653 - - 0.713	Dark grey organic clay As2 Th¹ 2	3	0	2	0	1
180 – 203	- 0.713 - - 0.943	Peat Th¹ 4	3	0	2	1	3
203 – 310	- 0.943 - - 2.013	Blue grey sandy clay As3 Ga1	2	0	2	0	0
310 – 415	- 2.013 - - 3.063	Gun metal grey clay with coarse sand and organic flex A3 Gs1	2+	2	2	2	0
415 – 540	- 3.063 - - 4.313	Coarse sand with clay and shellsGs3 As1	2+	1	2	2	
PL6							
0 – 18	1.204 – 0.844	Topsoil	0	0	0	0	0
18 – 137	0.844 - - 0.346	Brown silty clay As2 Ag2	2	0	2	1	0
137 – 140	- 0.346 - - 0.376	Erosive contact containing peat and clay	0	0	0	0	0
140 – 165	- 0.376 - - 0.626	Th¹ 4 Dark woody peat very compacted	3+	0	1	0	0
165 – 169	- 0.626 - - 0.666	Clay layer AS2 Th¹2	2	1	1	1	1
169 – 196	- 0.666 - - 0.936	Th¹4 Woody peat	3+	0	1	0	0
196 – 227	- 0.936 - - 1.246	Blue grey clay As4 Ag+	1	1	1	1	3
227 – 414	- 1.246 - - 3.116	Clay with coarse sand As3 Gs1	2	3	2	3+	3
414 – 480	- 3.116 - - 3.776	Coarse sand Gs3 As1	2+	2	2	3	
PL7							
0 – 13	1.311 – 1.181	Topsoil	0	0	0	0	1
13 – 90	1.181 – 0.411	Hard oxidised silty clay As2 Ag2	3	0	4	3	1
90 – 128	0.411 – 0.031	Clay with silt and sand present As3 Ag1 Ga+	2	0	1	3	1
128 – 243	0.031 - - 1.119	Sand with orange bands Ga3 Ag1	2	2	1	0	1
243 – 469	- 1.119 - - 3.379	Dark grey/black sand Ga4 Sh⁴ +	4	0	3	0	
PL8							
0 – 13	2.002 – 1.872	Topsoil	0	0	0	0	0
13 – 171	1.872 – 0.292	Silty clay As2 Ag2 Lf* +	2	0	3	3	2
171 – 223	0.292 - -0.228	Dark brown woody well humified woody peat Tl4	3	0	0	0	2
223 – 670	-0.228 - - 4.698	Blue grey soft clay with organic flex As4 Sh⁴ +	2	0	3	3	
PL9							
0 – 16	2.112 – 1.952	Topsoil	0	0	0	0	1
16 – 97	1.952 – 1.142	Silty clay As2 Ag2 Lf* + Ga +	2	0	1	1	1
97 – 209	1.142 – 0.022	Grey sandy silty clay As2 Ga1 Ag1	2	0	2	1	2

209 – 413	0.022 - - 2.018	Sandy clayey silt Ag2 As1 Ga1	3	2	2	1	1
413 – 437	- 2.018 - - 2.258	Sand with silt and clay Ga2 As1 Ag1	2	2	2	1	

PL10

0 –16	1.96 – 1.8	Topsoil	0	0	0	0	1
16 – 100	1.8 – 0.96	Grey/brown silty clay As2 Ag2 Lf*+	2	0	1	2	1
100 – 200	0.96 - - 0.04	Silty clay As3 Ag1	1	0	3	3	1
200 – 205	-0.04 - - 0.09	Clay with silt present As4 Ag+	4	0	2	3	1
205 – 221	- 0.09 - - 0.25	Organic layer Sh⁴ 4	4	0	2	0	1
221 – 278	-0.25 - - 0.82	As4 Ag+ Sh⁴ +	4	0	2	3	1
278 – 328	- 0.82 - -1.32	Light grey clay As4	2	1	2	3	2
328 – 401	-1.32 - -2.05	Sandy silty clay gun metal grey with sand in bands As2 Ag1 Ga1	3	2	2	3	2
401 – 546	-2.05 - - 3.50	Dark grey sand Ga4	3	0	2	0	

PL11

0 – 16	2.095 – 1.935	Topsoil	0	0	0	0	1
16 – 152	1.935 – 0.575	Brown silty clay As2 Ag2 Lf*+	2	0	3	2	3
152 – 216	0.575 – - 0.065	Woody peat with *Menyanthes* and *Phragmites* visible Tl4	3	2	0	0	1
216 – 219	-0.065 - - 0.095	Transition silty peat Ag2 Tl2	2	0	0	0	0
219 – 296	- 0.095 - - 0.865	Blue grey silty clay As3 Ag1 Ga+	2	0	2	1	1
296 – 434	- 0.865 - - 2.245	Grey sand Ga4	2	2	2	2	1
434 – 680	- 2.245 - - 4.705	Sand with silt and clay Ga2 Ag2 As+	2	1	2	2	

PL12

0 – 7	1.945 – 1.875	Topsoil	0	0	0	0	1
7 – 17	1.875 – 1.775	Silty clay As2 Ag2 Lf*+	2	0	2	2	1
17 – 141	1.775 – 0.535	Silty clay with calcareous nodules As2 Ag2 Lf*+	2	0	2	2	2
141 – 175	-.535 – 0.195	Dark brown peat Dh4	4	0	0	0	3
175 – 270	0.195 - - 0.755	Blue grey clay As3 Ag1 Sh⁴+	2	1	2	2	1
270 – 361	- 0.755 - - 1.665	Silty clay with bands of sand and organic flex As2 Ag1 Ga1	2	2	3	2	2
361 – 521	- 1.665 - - 3.265	Gun metal grey sand and silt Ga2 Ag2	3	1	2	1	1
521 – 565	- 3.265 - - 3.705	Clay As4 Ag+ Ga+	2	0	3	3	0
565 – 605	- 3.705 - - 4.105	Sand and silt Ga2 Ag2	3	1	2	1	

PL13

0 – 7	2.015 – 1.945	Topsoil	0	0	0	0	1
7 – 194	1.945 – 0.075	Silty clay As2 Ag2 Lf*+ (rooty)	2	0	3	2	1
194 – 211	0.075 - - 0.095	Grey silty clay As3 Ag1 Ga+	3	0	2	3	2
211 – 225	- 0.095 - - 0.235	Dark brown detrital peat with *Menyanthes* and *Phragmites* Dh4	4	0	3	1	2
225 – 288	- 0.235 - - 0.865	Grey stratified clay with silt As3 Ag1 Th+	3	1	3	2	3
288 – 360	- 0.865 - - 1.585	Highly laminated sand and clay GA3 As1	3	3	3	1	2
360 – 482	- 1.585 - - 2.805	Grey laminated clayey sand Ga2 As2	3	2	2	2	2
482 – 500	- 2.805 - - 2.985	Dark grey/black silty clayey sand	3+	0	2	3	

PL21

0 – 25	1.914 – 1.664	Topsoil	0	0	0	0	1
25 – 145	1.664 – 0.464	Silty clay As2 Ag2	2	0	2	2	1
145 – 188	0.464 – 0.034	Brown woody peat Tl4	3	0	0	0	2
188 – 316	0.034 - - 1.246	Blue-grey silt and clay As2 Ag2	2	1	2	2	2
316 – 380	- 1.246 - - 1.886	Laminated sand in silty clay Ga2 As1 Ag1	3	3	1	0	2
380 – 440	- 1.886 - - 2.486	Grey coarse sand Gs4	3	0	1	0	

PL22

0 – 17	2.018 – 1.848	Topsoil	0	0	0	0	1
17 – 180	1.848 – 0.218	Silty clay As2 Ag2 Lf*+	2	0	2	2	2
180 – 190	0.218 – 0.118	Silty clay As2 Ag2	2	0	2	2	1
190 – 223	0.118 - - 0.212	Woody peat with some *Phragmites* Tl2 Th(Phra)2	3	0	0	0	2
223 - 588	- 0.212 - - 3.862	Silt and clay As2 Ag2	2	0	2	2	

PL23

0 – 20	1.922 – 1.722	Topsoil	0	0	0	0	1
20 – 118	1.722 – 0.742	Silty clay As2 Ag2 Lf*+	2	0	2	2	2
118 – 147	0.742 – 0.452	Silty clay with sand lenses As2 Ag2 Ga+	2	0	2	2	1
147 – 233	0.452 - -0.303	Silty clay with organic flex As2 Ag2 Sh4+	2	0	2	2	3
233 – 253	-0.303 - - 0.608	Woody peat Tl4	3	0	0	0	3
253 – 284	- 0.608 - - 0.918	Organic silt Ag3 Sh41	3	2	1	2	1
284 – 630	- 0.918 - - 4.378	Fine blue silty clay Ag1 As3	2	0	1	2	1
630 – 632	- 4.378 - - 4.398	Shell remains *Part. test.*					
632 – 668	- 4.398 - - 4.758	Clayey silt As1 Ag3	2	0	1	2	

PL24

0 – 30	1.932 – 1.632	Topsoil	0	0	0	0	0
30 – 175	1.632 – 0.152	Silty clay with organic bands As2 Ag2 Sh4+	2	0	2	2	3
175 – 186	0.152 – 0.072	Eroded peat and silty clay As1 Ag2 Tl1	2+	2	1	1	1
186 – 221	0.072 - - 0.278	Woody peat Tl4	3	0	0	0	3
221 – 322	- 0.278 - - 0.288	Silty clay As2 Ag2	2	0	2	2	

PL25

0 – 21	1.858 – 1.648	Topsoil	0	0	0	0	1
21 – 113	1.648 – 0.728	Silty clay As2 Ag2	3	0	0	0	1
113 – 201	0.728 - - 0.152	Woody peat with silty clay Tl2 As1 Ag1	3	0	0	0	1
201 – 394	- 0.152 - - 2.082	Blue organic silt Ag3 As1 Sh4+	2	0	2	3	2
394 – 569	- 2.082 - - 3.832	Blue-grey sandy clay and silt Ag3 Ga1 As+	2	0	2	3	2
569 – 674	- 3.832 - - 4.882	Blue silt with organic flex Ag4 Sh4 +	2	0	2	3	2
674 – 700	- 4.882 - - 5.142	Pale white-grey silt with sand As2 Ga2	1	0	2	0	

PL26

0 – 17	1.766 – 1.156	Topsoil	0	0	0	0	1
17 – 188	1.156 - - 0.114	Silty clay As2 Ag2Lf*+	2	0	2	2	1
188 – 216	- 0.114 – -	Diffuse peat contact Well humified	3	0	0	0	1

	0.394	woody/rooty peat Th(Phra)2 Tl2					
216 – 252	- 0.114 – - 0.754	Brown woody peat Tl4	2	0	0	0	1
252 – 255	- 0.754 – - 0.784	Silty peat Ag2 Tl2	2	0	0	0	1
255 – 454	- 0.784 - - 2.774	Blue silt with organic and minerogenic flex As3 Ag1 Sh1+	2	1	2	3	2
454 – 489	- 2.774 - - 3.124	Pale grey silt with organic flex As4 Sh1+	1	1	2	3	2
489 – 693	- 3.124 - - 5.164	Dark grey sandy silt Ga2 As2	2	0	1	2	
PL27							
0 – 21	1.674 – 1.464	Topsoil	0	0	0	0	1
21 – 164	1.464 – 0.034	Silty clay As2 Ag2	2	0	2	2	1
164 – 200	0.034 - - 0.326	Grey blue silt with organic flex Ag3 Sh1+	2	0	2	2	2
200 – 300	- 0.326 - - 1.326	Blue-grey sand and silt Ga2 Ag2	3	0	0	0	1
300 – 328	- 1.326 - - 1.606	Laminated sand and silt Ga2 Ag2	3	3	1	1	
PL28							
0 – 21	1.904 – 1.694	Topsoil	0	0	0	0	1
21 – 160	1.694 – 0.304	Oxidised silty clay As2 Ag2	2	0	1	1	2
160 – 226	0.304 - - 0.356	Diffuse peat contact Th(Phra)2 Tl2	3	0	0	0	1
226 – 689	- 0.356 - - 4.986	Blue grey organic silt Ag2 As1 Th1	2	0	0	1	
PL29							
0 – 17	2.370 – 2.2	Topsoil	0	0	0	0	1
17 – 179	2.2 – 0.58	Silty clay As2 Ag2	2	0	1	1	2
179 – 302	0.58 - - 0.65	Black organic silt Ag3 As1 Th+	3	0	2	1	1
302 – 328	- 0.65 - - 0.91	Grey organic silt Ag3 As1	2	0	3	3	2
328 – 369	- 0.91 - - 1.32	Grey laminated sandy silt Ag3 Ga1	2	2	3	2	2
369 – 376	- 1.32 - - 1.39	Dark grey organic silt Ag3 Sh11	3	0	2	1	1
376 – 528	- 1.39 - - 2.91	Laminated grey sandy silt Ga2 As1 Ag1	2	2	3	1	
PL30							
0 – 16	1.795 – 0.635	Topsoil	0	0	0	0	1
16 – 85	1.635 – 0.945	Silty clay As2 Ag2	2	0	1	1	1
85 – 171	0.945 – 0.085	Crumbly peat Tl4	3	0	1	0	1
171 – 255	0.085 - - 0.755	Blue grey silty clay As3 Ag1	2	0	2	3	2
255 – 474	- 0.755 – - 2.945	Clay with organic flex As3 Ag1 Sh1+	3	1	3	1	2
474 – 499	- 2.945 - - 3.195	Grey slightly sandy with limus fragments Ga3 Lf1	2	2	1	1	
PL31							
0 – 20	1.584 – 1.384	Topsoil	0	0	0	0	1
20 – 92	1.384 – 0.664	Silty clay As2 Ag2	2	0	2	2	1
92 – 170	0.664 - - 0.116	*Phragmites* peat and detritus Th(Phra)2 Dl2	3	0	0	0	3
170 – 175	- 0.116 - - 0.166	Contact					
175 – 223	- 0.166 - - 0.646	Silt with some clay As1 Ag3 Ga+	2+	1	3	1	0
223 – 254	- 0.646 - - 0.956	Sandy silt with organic staining Ga2 Ag2	2+	2	1	2	2
254 – 295	- 0.956 - - 1.366	Sand and gravel Ga2 Gg(min)2	2	0	0	0	

Stratigraphic descriptions for the Canche Estuary, NW France

CA1

Depth (m)	Depth NGF	Description and Components	Nig	Strf	Sicc	Elas	Lim supp
0 – 20	3.86 – 3.66	Topsoil	3	0	4	0	2
20 – 138	3.66 – 2.48	Laminated silt and sand Ga3 Ag1	2	0	4	0	1
138 – 246	2.48 – 1.4	Dark grey organic silt and sand Th+ Ag2 Gs2	2	2	2	1	1
246 – 248	1.4 – 1.38	Shell fragments in sandy silty clay As2 Ag1 Ga1 *Part. test.*	2	0	2	1	1
251 – 299	1.38 – 0.87	Coarse sand Gs4	3	0	2	0	1
299 – 312	0.87 – 0.74	Silty organic sand Ga3 Ag1 Th+ As+	2+	0	2	0	2
312 – 329	0.74 – 0.56	Clayey organic silt Ag2 As1 Ga1 Th+	3	0	2	1	1
329 – 561	0.56 - - 1.75	Sandy organic silt Ga2 Ag2 Th+	2	0	2	0	

CA2

0 – 22	4.6 – 4.38	Topsoil	-	-	-	-	3
22 – 83	4.38 – 3.77	Light brown loam Ag2 Ga1 As1	2	-	4	1	1
83 – 131	3.77 – 3.29	Sandy clayey silt Ag2 Ga1 As1	2	-	4	1	2
131 – 200	3.29 – 2.6	Sandy with some silt Ga3 Ag1 As+	2	-	2	0	

CA5

0 – 25	4.14 – 3.89	Topsoil	-	-	-	-	1
25 – 522	3.89 - - 1.08	Sand Ga4	2	0	4	0	

CA8

0 – 20	4.16 – 3.96	Topsoil	-	-	-	-	1
20 – 85	3.96 – 3.31	Sandy silt Ga2 Ag2 *Part.test*	2	0	3	0	1
85 – 169	3.31 – 2.47	Sandy clayey silt Ag2 Ga1 As1	2	0	2	0	2
169 – 175	2.47 – 2.41	Silt and clay Ag2 As2 Ga+	2	0	2	0	2
175 – 251	2.41 – 1.65	Grey sand Ga4	2+	0	2	0	4
251 – 276	1.65 – 1.4	Woody peat Tl4	3	-	-	-	1
276 – 283	1.4 – 1.33	Sandy clayey silt Ag3 As1 Ga+	3	-	-	-	1
283 – 383	1.33 – 0.33	Sand and silt Ga2 Ag2	2+	0	2	1	

CA6

0 – 30	4.29 – 3.99	Strf. Conf	-	-	-	-	1
30 – 123	3.99 – 3.06	Sand with silt Ga4 Ag+	2+	0	3	0	1
123 – 280	3.06 – 1.49	Sand with silt and clay Ga2 As1 Ag1	2	-	1	-	1
280 – 282	1.49 – 1.47	Sandy peat Ga1 $Th^1 3$	3	-	-	-	2
282 – 312	1.47 – 1.17	Detrital peat Dh2 Tl2	3	-	-	-	1
312 – 320	1.17 – 1.09	Sandy peat Dl3 Ga1	2	-	-	-	1
322 – 500	1.09 - - 0.71	Silty sand Ga3 Ag1	2	-	-	-	

CA4

0 – 53	4.20 – 3.67	Strf. Conf.	2	0	3+	0	1
53 – 249	3.67 – 1.71	Grey sandy silt with organic flex Ag3 Ga1 As+ Sh+	2	0	3	0	3
249 – 255	1.71 – 1.65	Organic turfa $Th^1 4$	3	-	-	-	2
255 – 259	1.65 – 1.61	Grey brown organic silt Ag3 $Th^1 1$	2	-	-	-	2
259 – 282	1.61 – 1.38	Detritus and turfa Dl1 $Th^1 3$	2	-	-	-	2
282 – 312	1.38 – 1.08	Blue grey clay with silt As3 Ag1 *Test.*	2+	0	2	2	2
312 – 385	1.08 – 0.35	Detritus woody peat Dl1 Tl3	3+	0	0	0	1
385 - 480	0.35 - - 0.6	Sand with silt Ga3 Ag1 (molluscs)	2	0	1	0	

Canche
Sample

0 – 7	4.39 – 4.13	Topsoil	-	-	-	-	1
7 – 175	4.13 – 2.45	Pale sandy silt with organic flex Ag3 Ga1 Th+	2	0	3	0	2
175 – 222	2.45 – 1.98	Grey sandy silt Ag3 Ga1	2	0	3	0	2
222- 239	1.98 – 1.81	Organic turfa Sh^4 4	3	0	0	0	2
239 – 312	1.81 – 1.08	Grey sandy silt with organic flex Ag2 Ga2	2+	1	3	0	1
312 – 325	1.08 – 0.95	Silty peat Ag2 Sh^4 2	2+	-	-	-	1
325 – 367	0.95 – 0.53	Dark brown woody peat Tl4	3	-	-	0	1
367 – 376	0.53 – 0.44	Blue sandy silty clay with organic flex As2 Ag1 Ga1 *Part. test*	2+	0	2	1	1
376 – 410	0.44 – 0.104	Blue grey sandy silty clay Ga1 Ag1 As2	3	0	3	1	1
410 – 491	0.104 - -0.70	Grey sand Ga3 Ag1	3+	0	3	0	

CA3

0 – 38	4.17 – 3.79	Topsoil	-	-	-	-	1
38 – 78	3.79 – 3.39	Silt with sand and clay Ag4 Ga+ As+	1	-	4	0	2
78 – 240	3.39 – 1.77	Sand and silt with organic bands	2	1	3	0	1
240 – 268	1.77 – 1.49	Organic silty sand Ga3 Ag1 Th^1+	3	3	3	0	2
268 – 270	1.49 – 1.47	Organic turfa $Th^1$4	3	-	-	-	3
270 – 273	1.47 – 1.44	Sand with clay Ga3 As1	3	0	3	1	3
273 – 281	1.44 – 1.36	Detritus Dl2 Dh2	2				2
281 – 286	1.36 – 1.31	Sandy clay As3 Ga1	2+	0	0	3	2
286 – 299	1.31 – 1.18	Detritus Dl2 Dh2	2	-	-	-	2
299 – 350	1.18 – 0.67	Sand and peat layers Dh1 Dl1 Ga2	2+	2	3	0	-
350 – 363	0.67 – 0.54	Disturbed silty peat contact	-	-	-	-	-
363 – 390	0.54 – 0.27	Grey sandy silt Ga2 Ag2	2	0	3	0	

CA7

0 – 20	4.06 – 3.86	Strf. Conf	-	-	-	-	1
20 – 160	3.86 – 2.46	Pale blonde sand with silt Ga3 Ag1	1	0	4	0	1
160 – 241	2.46 – 1.65	Grey silty sand Ga3 Ag1+	2+	0	2	0	3
241 – 242	1.65 – 1.64	Peat $Sh^4$4	3	-	-	-	3
242 – 250	1.64 – 1.56	Sand with clay Ga3 As1					
250 – 251	1.56 – 1.55	Woody peat Tl4					
251 – 260	1.55 – 1.46	Sand with silt and clay Ga3 Ag1 As1	2+	0	2	-	2
260 – 264	1.46 – 1.42	Woody peat Tl4	3	-	-	-	1
264 – 280	1.42 – 1.26	Organic silty clay As2 Ag2 Dh+	3	1	-	-	1
280 – 281	1.26 – 1.25	Woody peat Tl4	3	1	-	-	1
281 – 303	1.25 – 1.03	Oragnic silty clay As2 Ag2 Dh+	3+	1	-	-	1
303 – 304	1.03 – 1.02	Organic silty clay Dh1 As2 Ag1	3+	1	-	-	1
304 – 385	1.02 – 0.21	Dark brown woody peat Tl4	3+	-	-	-	2
385 – 409	0.21 - -0.03	Sandy silt Ag3 Ga1 *Part test*	2+	-	-	-	1
409 – 457	-0.03 - -0.51	Sand and silt Ga2 Ag2 Dh+	2+	-	-	-	-
457 – 470	-0.51 - -0.64	Herbaceous peat Th4 – possibly erosive	3+	-	-	-	3
470 - 490	-0.64 - -0.84	Sand with organic flex Ga4 Dh+	2+	-	-	-	

CA9

0 – 15	4.44 – 4.425	Strf. Conf	-	-	-	-	1
15 – 157	4.425 – 2.87	Sand with silt Ga4 Ag+	2	-	3	0	1
157 – 223	2.87 – 2.21	Sand and silt Ga3 Ag1	2	0	2	0	1

223 – 246	2.21 – 1.98	Organic sandy silt	2+	0	2	0	3
246 – 249	1.98 – 1.95	Peat transition Tl4	3	-	-	-	1
249 – 264	1.95 – 1.8	Black peat Th¹4	4	-	-	-	3
264 – 297	1.8 – 1.47	Woody peat Tl4	3	-	-	-	2
297 – 299	1.47 – 1.45	Black peat Th¹4	4	-	-	-	2
299 – 375	1.45 – 0.69	Woody peat Tl4	3	-	-	-	1
375 – 390	0.69 – 0.54	Transition	2	-	-	-	1
390 – 420	0.54 – 0.24	Organic clayey silt Ag4 Th+ As+	2	0	2	1	1
420 – 470	0.24 - -0.26	Sand Ga4	2+	0	0	0	

CA10

0 – 33	5.2 – 1.87	Strf. Conf	-	-	-	-	1
33 – 90	4.87 – 4.3	Pale brown silt with fine sand Ag3 Ga1	2	0	3	0	1
90 – 114	4.3 – 1.06	Brown organic turfa with *Phragmites* Th(Phra) 3 Ag1	3	1	3	1	1
114 – 177	4.06 – 3.43	Th(Phra) 3 Ag1+ silty	2+	0	2	0	1
177 – 215	3.43 – 3.05	Woody peat Tl4	3+	0	3	0	1
215 – 231	3.05 – 2.89	Th (Phra) 4	2	0	2	0	1
231 – 295	2.89 – 2.25	Silt with sand Ag3 Ga1	2	0	2	0	1
295 – 334	2.25 – 1.86	Silty Ag4 As+ Ga+	2	0	2	3	1
334 – 345	1.86 – 1.75	Olive green silty clay As2 Ag2	2	0	2	3	1
345 – 360	1.75 – 1.60	Olive green sandy clay As2 Ga2	2	0	2	2	1
360 – 382	1.60 – 1.38	Sand Ga4 As+ Ag+	2	0	1	1	

CA11

0 – 13	5.56 – 5.54	Strf. Conf	-	-	-	-	1
13 – 106	5.54 – 4.5	Very hard sand Ga3 Ag1 *Part test*	2	-	-	-	-

Stratigraphic descriptions for the Somme Estuary, NW France

SO1

Depth (m)	Depth NGF	Description and Components	Nig	Strf	Sicc	Elas	Lim supp
0 – 90	6.54 – 5.64	Th¹ 4 turfa	3+	0	2	-	1
90 – 92	5.64 – 5.62	Silt with organic turfa Ag3 Th¹1	3	0	2	-	1
92 – 271	5.62 – 3.83	Organic turfa Th¹4	4	0	2	-	3
271 – 288	3.83 – 3.66	Light grey/white silty clay As3 Ag1	1	0	4	3	

SO2

0 – 12	6.56 – 6.54	Th¹4 turfa	-	-	-	-	1
12 – 20	6.54 – 6.36	Grey organic clay As3 Ag1	2+	0	2	2+	3
20 – 180	6.36 – 4.76	Well humified wet peat Dl2 Tl2	3	-	-	-	1
180 – 183	4.76 – 4.73	Organic sand Ga2 Th¹2	2+	-	-	-	2
186 – 185	4.73 – 4.71	Sandy turfa Th¹3 Ga1	2+	0	-	0	1
185 – 199	4.71 – 4.57	Organic sand Ga3 Th¹1	2+	0	-	0	1
199 – 228	4.57 – 4.28	Sand light brown Ga4	2+	1	1	1	1
228 – 229	4.28 – 4.27	Black sand Ga4	4	0	-	0	2
229 – 247	4.27 – 4.09	Brown-grey sand Ga4	3+	0	-	0	2
247 – 250	4.09 – 4.06	Woody peat Dl4	4	0	-	0	2
250 – 252	4.06 – 4.04	Sand Ga4	3+	0	-	0	2
252 – 260	4.04 – 3.96	Sandy detritus Ga1 Dl3	3	0	-	0	1
260 – 310	3.96 – 3.46	Sandy peat Ga2 Dl2	3	0	-	0	1
310 – 347	3.46 – 3.09	Pale brown sand Ga4	2	0	2	0	

SO5

0 – 10	4.67 – 4.66	Strf. Conf.	4	-	-	-	1
10 – 42	4.66 – 4.25	Undifferentiated organic deposit with sand Sh^{4}3 Ga1	3	0	2	0	2
42 – 43	4.25 – 4.24	Wood fragments Tl4	-	-	-	-	3
43 – 187	4.24 – 2.80	Sand with organic flex Ga4 Dh+	2+	0	2	0	2
187 – 300	2.80 – 1.67	Coarse orange sand Gs4	3	0	2	0	2
300 – 305	1.67 – 1.37	White sticky solifluction deposit	1	0	1	2	

SO6

0 – 39	5.65 – 5.26	Undifferentiated organic matter Sh^{4}4	3	0	2	0	1
39 – 182	5.26 – 3.83	Grey sand Ga4	4	0	1	3	3
182 – 25	3.83 – 3.15	White sticky solifluction deposit	1	0	0	0	

SO4

0 – 24	4.45 – 4.21	Strf Conf	3	-	-	-	2
24 – 37	4.21 – 4.08	Silt with sand and clay Ag2 Ga1 As1 *Part test*	2+	0	3	2	2
37 – 144	4.08 – 3.01	Grey sand with clay Ga3 As1	2	0	3+	0	2
144 – 187	3.01 – 2.58	Grey silty sand Ga2 As1 Ag1	2	0	2	1	1
187 – 272	2.58 – 1.73	Sandy silty clay with organic flex As2 Ag1 Ga1	2+	0	2	3	2
272 – 277	1.73 – 1.68	Brown grey clay with silt and organic flex As3 Ag1 Th^1+	2+	0	3	3	2
277 – 306	1.68 – 1.39	Well humified detritus Dl4	3+	0	3+	0	3
306 – 341	1.39 – 1.04	Dl4 *Part test*	3	0	3+	0	4
341 – 515	1.04 – -0.7	Dl4 No molluscs	3+	0	3+	0	1
515 – 520	-0.7 – -0.75	Dl4 *Part test*	3	0	3	0	1
520 – 537	-0.75 – -0.92	Dl4 no molluscs	3+	0	3	0	

SO7

0 – 26	3.012 – 2.75	Undifferentiated organic matter Sh^{4}4	3	0	1	0	4
26 – 95	2.75 – 2.06	Pale grey sand Ga4 *Part test*	1	0	2	0	1
95 – 169	2.06 – 1.32	Dark grey organic sand Ga4 Dh+	2	0	2	0	1
169 – 216	1.32 – 0.85	Sand and peat Ga2 Th2	3	0	0	-	1
216 – 219	0.85 – 0.82	Peat Tl4	3	0	0	-	1
219 – 220	0.82 – 0.81	Sand Ga4	2	0	0	-	3
220 – 226	0.81 – 0.75	Organic sand Sh^{4}2 Ga2	3	2	0	-	1
226 – 254	0.75 – 0.47	Dark brown herbaceous peat Th^{4}4	4	-	-	-	2
254 – 269	0.47 – 0.32	Pale brown sandy peat Ga1 Th3	3	-	-	-	3
269 – 292	0.32 – 0.092	Grey silty clay As3 Ag1 Ga+	2	-	-	-	3
292 – 428	0.092 – -1.268	Woody peat Tl4					

SO8

0 – 10	2.25 – 2.15	Strf. Conf	-	-	-	-	1
10 – 61	2.15 – 1.64	Grey brown sand Ga4	2	-	-	-	2
61 – 81	1.64 – 1.44	Sandy silty clay As2 Ag1 Ga1	2	-	-	-	1
81 – 296	1.44 - -0.71	Grey/black organic sand Ga4 Dh+	3	-	-	-	3
296 – 348	-0.71 - - 1.23	Woody peat Tl4	4	-	-	-	1
348 – 353	- 1.23 - - 1.28	Light brown sandy detritus Dh3 Ga1	3	-	-	-	2
353 – 360	- 1.28 - - 1.35	Sand and silt Ga2 Ag2	2	-	-	-	2
360 – 364	- 1.35 - - 1.39	Sand and clay Ga2 As2	1	-	-	-	2
364 – 368	- 1.39 - - 1.43	Silt and sand Ag3 Ga1	3	-	-	-	2
368 – 386	- 1.43 - - 1.61	Grey silty sandy clay As2 Ag1 Ga1 Dh+	2	-	-	-	1
386 – 398	- 1.61 - - 1.73	Ga1 Ag1 As1 Dh1 *Part test*	2	-	-	-	1
398 – 405	- 1.73 - - 1.80	Herbaceous detritus Dh3 Th (Phra) 1	4	-	-	-	3
405 – 407	- 1.80 - - 1.82	Organic sand Ga3 Th1	3	-	-	-	2
407 - 417	- 1.82 - - 1.92	Sandy silty peat Ga1 Ag1 Th2	2	-	-	-	2
417 – 432	- 1.92 - - 2.07	Grey sand Ga4	2	-	-	-	1
432 – 510	- 2.07 - - 2.85	Blue-grey sandy clay Ga1 As3	2	-	-	-	

SO3

0 – 16	4.96 – 4.80	Strf. Conf.	3	0	4	0	1
16 – 65	4.80 – 4.31	Silt with sand and clay Ag3 As1 Ga+	2+	0	3	0	2
65 – 106	4.31 – 3.90	Silt and sand Ag3 Ga1 As+	2+	0	3	0	2
106 – 303	3.90 – 1.93	Sand Ga4	2+	0	-	0	1
303 – 410	1.93 – 0.86	Dl2 Tl2	3	-	-	-	3
410 – 432	0.86 – 0.64	Blue grey silty clay As2 Ag2	2+	2	2	2	-
432 – 474	0.64 – 0.22	Detrital peat Dl2 Tl2	3+	-	-	-	4
474 – 746	0.22 - - 2.5	Blue grey silty clay As2 Ag1	2+	2	2	2	-
746 – 879	- 2.5 - - 3.83	Grey sandy clay As3 Ga1	2+	2	2	2	

SO9
Sample

0 – 27	4.26 – 3.99	Strf. Conf.	-	-	-	-	1
27 – 87	3.39 – 3.99	Sand with undifferentiated organic matter Ga3 Sh1	3	-	-	-	2
87 – 112	3.39 – 3.14	Silty sandy clay As2 Ag1 Ga1	2	-	-	-	2
112 – 146	3.14 – 2.80	Upper woody peat Th2 Tl2	2	-	-	-	2
146 – 179	2.80 – 2.47	Sandy peat Ga2 Dh2	2	-	-	-	2
179 – 320	2.47 – 1.06	Detrital peat Gh3 Dl1	4	-	-	-	1
320 – 327	1.06 - 0.99	Transition from sand to detrital peat Th2 Ga2	2	-	-	-	1
327 – 430	0.99 - - 0.10	Sand Ga4	3	-	-	-	1
430 - 460	- 0.10 - - 0.40	Lower woody Peat Tl3 Ga1	4	-	-	-	2
460 – 500	- 0.40 - - 0.80	Sand Ga4	3	-	-	-	1
500 – 540	- 0.80 - - 1.10	Lower peat Tl4	4	-	-	-	2
540 - 560	- 1.10 - - 1.30	Lower sand Ga4	3	-	-	-	

SO10

0 – 39	4.62 – 4.23	Sand with silt and clay Ga2 Ag1 As1	2	0	-	2	1
39 – 54	4.23 – 4.08	Grey brown sand Ga3 Ag1 As+	1	0	-	1	1
54 – 115	4.08 – 3.58	Silt and sand Ag2 Ga2	1	+	-	2+	1
115 – 126	3.58 – 3.36	Clay and silt with sand As2 Ag2 Ga+	+	0	-	3	0
126 – 127	3.36 – 3.35	Sand silt and clay Ga1 Ag1 As1	1	0	-	2	3
127 – 144	3.35 – 3.18	Peat Tl4	4	1	-	-	3+
144 – 146	3.18 – 3.16	Silty peat Tl3 Ag1	3	2	-	2	2
146 – 207	3.16 – 2.55	Sand with silt Ga3 Ag1Th(Phra)+	1	0	-	1	3
207 – 219	2.55 – 2.43	Silt with sand and clay Ag2 As1 Ga1	2	0	-	2	1
219 – 220	2.43 – 2.42	Ga3 Ag1	2+	0	-	0	4
220 – 223	2.42 – 2.39	Silt and clay Ag2 As2 Ga+	2+	1	-	0	2
223 – 226	2.39 – 2.36	As3 Ag1 Th(Phra)+	2+	0	-	3	3
226 – 228	2.36 – 2.34	As3 Ag1	2++	2	-	3	3
228 – 259	2.34 – 2.03	*Phragmites* peat Th(Phra)4	3+	+	-	1	1
259 – 270	2.03 – 1.92	As3 Ag1	2	2	-	3	4
270 – 303	1.92 – 1.59	Th(Phra)1 Dl3	4	0	-	0	1
303 – 380	1.59 – 0.82	Tl1 Dh3	4	0	-	0	2
380 – 396	0.82 – 0.66	Th2 Ag2 Silty peat	3	1	-	3	2
396 – 416	0.66 – 0.46	Blue grey silty clay Ag+ As4	1	0	-	4	0
416 – 434	0.46 – 0.28	Th4 Ag+	3+	0	-	2	1
434 - 450	0.28 – 0.12	Blue-grey Ga3 Ag1	1	0	-	0	-

Appendix III

Results from the diatom-based transfer function for the Canche

Taxon	Fossil			Modern		
	N	N2	Max	N	N2	Max
Al	10	4.96	13.04	0	0	0
Ad	8	4.88	32.26	75	30.64	87.5
AS	15	12.61	8.06	47	29.11	7.03
Ag	4	2.63	6.45	0	0	0
cw	3	2.97	1.69	35	12.65	16.41
Cp	6	4.14	7.85	0	0	0
Cs	5	3.79	7.5	52	28.99	13.58
Cr	6	3.5	5	0	0	0
Ck	1	1	13.54	0	0	0
Cs	1	1	2.38	52	28.99	13.58
Dc	6	2.18	17.24	0	0	0
Dd	13	3.5	20.83	26	10.81	8.89
Ds	4	1.68	8.47	19	4.65	22.93
Dn	10	4.74	11.46	12	1.58	31.64
ep	2	1.16	8.93	7	4.77	2.66
Fb	2	1.96	2.38	0	0	0
Hv	4	2.49	4.32	0	0	0
Ni	4	2.26	12.5	67	18.48	44.48
Nf	3	2.14	5.38	22	6.9	25.78
N1	4	1.58	15.62	56	24.86	17.59
OP	10	3.9	20.16	45	14.05	23.42
OM	10	5.57	30.43	0	0	0
PS	22	17.92	93.51	78	39.08	21.88
Pc	6	4.15	27.08	11	3.29	45.34
Pd	7	4.82	2.5	0	0	0
Pw	16	8.87	48.28	0	0	0
Ra	17	11.64	8.63	40	21.26	12.79
Rt	3	1.51	9.52	0	0	0
Sy	2	1.59	4.35	0	0	0
Tn	6	3.05	13.56	14	3.49	7.81

Appendix IV

The following results detail the estimations of sediment compaction that were calculated for each sea-level index points using Allen's (1999) equation:

$$T = (T_0 - T_{min})e^{-KH} + T_{min}$$

where:
T = Present thickness
To = Original thickness
Tmin = Limiting thickness
e = constant
k = compressibilty of sediment
H = overburden

Pevensey Levels Sample Core		**Pevensey Levels - other cores**	
Bottom of peat		**Pevensey Levels BH-4 Top of peat**	
T	ASSUME NO COMPACTION	T	0.25
a		a	0.219
e		e	2.718
k		k	0.537
H		H	2.86
To		To	0.646
(To-T)		(To-T)	0.396
Top of peat		**Pevensey Levels BH-3 Bottom of peat**	
T	0.45	T	ASSUME NO COMPACTION
a	0.219	a	
e	2.718	e	
k	0.537	k	
H	1.95	H	
To	0.913	To	
(To-T)	0.463	(To-T)	
Top of silty clay		**Pevensey Levels BH 25 Bottom of peat**	
T	0.03	T	ASSUME NO COMPACTION
a	0.6	a	
e	2.718	e	
k	0.361	k	
H	1.69	H	
To	0.037	To	
(To-T)	0.007	(To-T)	
Top of peat		**Pevensey Levels BH25 Top of peat**	
T	0.3	T	0.88
a	0.219	a	0.219
e	2.718	e	2.718
k	0.537	k	0.537
H	1.62	H	1.13
To	0.549	To	1.365
(To-T)	0.249	(To-T)	0.485
Top of upper silty clay			
T	1.41		
a	0.6		
e	2.718		
k	0.361		
H	0.21		
To	1.452		
(To-T)	0.042		

Canche Sample core		Canche BH9	
Bottom of peat		**Bottom of peat**	
T	ASSUME NO COMPACTION	T	ASSUME NO COMPACTION
a		a	
e		e	
k		k	
H		H	
To		To	
(To-T)		(To-T)	
Top of peat		**Top of peat**	
T	0.13	T	1.26
a	0.219	a	0.219
e	2.718	e	2.718
k	0.537	k	0.537
H	3.12	H	2.46
To	0.356	To	2.948
(To-T)	0.226	(To-T)	1.688
Bottom of upper peat		**Canche BHCA10 Bottom of peat**	
T	1.03	T	ASSUME NO COMPACTION
a	0.6	a	
e	2.718	e	
k	0.361	k	
H	2.39	H	
To	1.3397	To	
(To-T)	0.3097	(To-T)	
Top of upper peat		**Top of peat**	
T	0.17	T	2.05
a	0.219	a	0.219
e	2.718	e	2.718
k	0.537	k	0.537
H	2.22	H	0.9
To	0.373	To	2.926
(To-T)	0.203	(To-T)	0.876
Somme Sample Core		**SO BH8**	
Bottom of peat		**Bottom of peat**	
T	ASSUME NO COMPACTION	T	ASSUME NO COMPACTION
a		a	
e		e	
k		k	
H		H	
To		To	
(To-T)		(To-T)	
Top of peat		**Top of peat**	
T	0.4	T	0.07
a	0.219	a	0.219
e	2.718	e	2.718
k	0.537	k	0.537
H	5	H	3.98
To	1.469	To	0.225
(To-T)	1.069	(To-T)	0.155

Bottom of peat		**Bottom of upper peat**	
T	ASSUME NO COMPACTION	T	0.5
a		a	0.6
e		e	2.718
k		k	0.361
H		H	3.48
To		To	0.7004
(To-T)		(To-T)	0.2004
Top of peat			
T	0.3		
a	0.219		
e	2.718		
k	0.537		
H	4.3		
To	1.011		
(To-T)	0.711		
Bottom of peat			
T	ASSUME NO COMPACTION		
a			
e			
k			
H			
To			
(To-T)			
Top of peat			
T	1.41		
a	0.219		
e	2.718		
k	0.537		
H	1.79		
To	2.724		
(To-T)	1.314		
Bottom of peat			
T	Assume no compaction		
a			
e			
k			
H			
To			
(To-T)			
Top of peat			
T	0.34		
a	0.219		
e	2.718		
k	0.537		
H	1.12		
To	0.525		
(To-T)	0.185		
Bottom of diff. Organic matter			
T	0.25		
a	0.6		
e	2.718		
k	0.361		
H	0.87		
To	0.2802		
(To-T)	0.0302		